UNCLASSIFIED

AD NUMBER

AD805427

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; DEC 1966. Other requests shall be referred to Air Force Materials Laboratory, ATTN: MAAE, Wright-Patterson AFB, OH 45433.

AUTHORITY

AFML ltr dtd 12 Jan 1972

THIS PAGE IS UNCLASSIFIED

AFML-TR-66-264

STAINLESS-STEEL-LINED, GLASS-FILAMENT-WOUND TANKS FOR PROPELLANT STORAGE

805427

M. J. Sanger, R. Molho, E. E. Morris
Aerojet-General Corporation

TECHNICAL REPORT AFML-TR-66-264

December 1966

FILE COPY

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Materials Laboratory, MAAE, Wright Patterson Air Force Base, Ohio 45433

Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

34

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Copies of this report should not be returned to the Research and Technology Division unless return is required by security considerations, contractual obligations, or notice on a specific document.

(6) STAINLESS-STEEL-LINED, GLASS-FILAMENT-WOUND TANKS FOR PROPELLANT STORAGE.

(9) Technical rept. Jan-Jul 66,

(10) M. J. Sanger, R. Molho, E. E. Morris

(14) 3243

(15) AF 33(615)-3619

(16) AF-7381

(17) 738101 (18) AFML (19) TR-66-264

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Materials Laboratory, MAAE, Wright-Patterson Air Force Base, Ohio 45433

(11) Dec 66

(12) 50p.

1473
elf

ml

(007 000)

FOREWORD

This report was prepared by the Chemical and Structural Products Division, Von Karman Center, Aerojet-General Corporation, Azusa, California under USAF Contract No. AF 33(615)-3619. The contract was initiated under Project No. 7381, Task No. 738101, and BPSN No. 66(687381-738101-62405514). The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, Mr. T. J. Reinhart, Jr., Project Engineer.

This report covers work conducted from January to July 1966 and is submitted in fulfillment of the contract. The manuscript was released by the authors in July 1966 for publication as an RTD technical report.

The study was conducted under the direction of M. J. Sanger, Program Manager, and the supervision of F. J. Darms, Head of the Advanced Composites Section. Others who cooperated in the study and in the preparation of this report were S. B. Fabeck, Manager, Composite Structures Department; R. Molho, Design Engineer; and E. E. Morris, Design Engineer. This report is catalogued by Aerojet-General as Report No. 3243.

This technical report has been reviewed and is approved.

Albert O Levitch

Albert Olevitch, Chief
Materials Engineering Branch
Materials Applications Division

ABSTRACT

This work was undertaken to provide information on the design and fabrication of metal-lined, filament-wound, storable-propellant tanks and to conduct static and dynamic tests to validate the recommended materials and fabrication techniques.

A computer study was used in designing the head contours for the tanks to achieve maximum compatibility between the strains in the liner and the glass-filament overwrap. The head sections were reinforced with cap-type doilies.

Four 12-in.-dia by 38.68-in.-long tanks were fabricated with the same materials and processing techniques as those used under Contract AF 33(616)-1671, in which their feasibility was demonstrated.

Hydroburst, pressure-fatigue, and environmental-storage tests were satisfactorily conducted. They demonstrated that the metal-lined filament-wound tanks had the design burst strength, and that they can tolerate the pressure cycling and sustained loading required of storable-propellant tankage.

TABLE OF CONTENTS

		PAGE
I.	Introduction	1
II.	Summary	2
III.	Design (Task I)	3
	1. Computer Study	3
	2. Tank Design	5
	3. Design Analysis	5
	4. Weight Analysis	11
IV.	Fabrication (Task II)	12
	1. Liner	12
	2. Tank Assembly	15
V.	Test Program (Task III)	25
	1. Hydroburst	25
	2. Fatigue Cycling	28
	3. N_2O_4 Storage	32
VI.	Conclusions	33
VII.	Recommendations for Future Work	34
Appendix I	Head-Reinforcement Analysis and Calculations	39
Appendix II	Design Analysis	43
Document Control Data - R&D (DD Form 1473)		

ILLUSTRATIONS

FIGURE		PAGE
1.	Liner Assembly, 12-in.-dia Tank (Dwg No. 178029)	6
2.	Tank Assembly (Dwg No. 178028)	7
3.	Head Reinforcement, Initial (Dwg No. 178097)	8
4.	Polar Boss, 12-in.-dia Tank (Dwg No. 177419)	9
5.	Head Reinforcement, Final (Dwg No. 178158)	10
6.	Welding Doubler, Boss (Dwg No. 178030)	13
7.	Tank Fabrication, Welding of Head Section to Boss	14
8.	Tank Fabrication, Liner After Insertion of Plaster	16
9.	Tank Fabrication, Cleaning of Liner	17
10.	Filament-Winding Shaft (Dwg No. T-120229)	19
11.	Tank Fabrication, Longitudinal Filament Winding	22
12.	Tank Fabrication, Hoop Filament Winding	23
13.	Instrumented Tank Before Hydroburst Test	26
14.	Tank 12-1, Pressure vs Hoop Deflection During Hydroburst	27
15.	Tank 12-4, Pressure vs Longitudinal Deflection During Fatigue Cycling	30
16.	Tank 12-4, Pressure vs Hoop Strain During Fatigue Cycling	31
17.	Operating-Pressure Performance, Metal-Lined Glass-Filament-Wound Tankage	36
18.	Operating-Pressure Performance, Metal Tanks vs Metal-Lined Filament-Wound Tanks	37

TABLES

TABLE		PAGE
1.	Design Criteria	4
2.	Dimensional and Material Parameters	4
3.	Tank 12-4, Pressure vs Longitudinal Deflection and Hoop Strain	29

SECTION I

INTRODUCTION

The feasibility of fabricating metal-foil-lined, filament-wound tankage was demonstrated by Aerojet-General in work under Contract AF 33(615)-1671 and was reported in AFML-TR-65-381.[1] Fatigue-cycling tests and environmental propellant-exposure tests showed the structural integrity and serviceability of this type of construction.

A scale-up from the 8-in.-dia oblate-spheroid chamber used in that work to a 12-in.-dia by 38.68-in.-long cylindrical tank in the present program was desired to permit additional evaluation of the bonded-metal-liner concept. In addition, the use of a higher operating pressure in testing would provide a more severe environment for a metal-foil-lined tank.

It was found in the earlier studies that excessive growth of subscale tanks during pressure cycling in the areas around the polar bosses caused local liner buckling. This high-strain condition was reduced somewhat in that program by the use of auxiliary reinforcements in the boss areas. In the current program, head contours specifically designed for metal-lined, filament-wound tankage further minimized localized strains.

The work reported here was undertaken to provide the Air Force design details and fabrication techniques for use in producing filament-wound tankage to contain storable propellants for 30 days at an operating pressure of 350 psi and a temperature of 110°F. It was performed by the Chemical and Structural Products Division of Aerojet-General in a three-task program: design studies, fabrication effort, and evaluation testing.

This final report summarizes the work performed and presents conclusions and recommendations for guidance in future work on filament-wound tankage for storable propellants.

---

[1] M. J. Sanger, R. Molho, and W. W. Howard, Exploratory Evaluation of Filament-Wound Composites for Tankage of Rocket Oxidizers and Fuels, Air Force Materials Laboratory Technical Report, January 1966.

SECTION II

SUMMARY

Four, stainless-steel-lined, filament-wound tanks for the containment of nitrogen tetroxide (N_2O_4) for 30 days at an operating pressure of 350 psi and a temperature of 110°F were designed, fabricated, and tested.

The work included preparation of engineering drawings and detailed manufacturing procedures for tank fabrication. The test program included burst, pressure-fatigue, and N_2O_4-storage tests.

In Task I, the design phase, the dimensional and material parameters of the tank were subjected to computer analysis to obtain head-contour coordinates and other design features. A design for the head reinforcements was also prepared and analyzed. The results were incorporated in the design of, and engineering drawings for, the metal liner and tank assembly.

Four tanks were fabricated in Task II with materials and processes identical to those used under Contract AF 33(615)-1671. The tank liners were produced from Type 347 stainless steel (347 SS) by roll-resistance seam welding of the component parts. Twelve-end, resin-impregnated, glass roving was used for the filament-wound overwrap in order to produce tanks with optimum weight for the specified service conditions. The tanks were subjected to single-cycle burst tests, fatigue tests, and cyclic-fatigue tests.

A hydroburst at 750 psi was obtained with one of the tanks; this value was very close to the design single-cycle burst pressure of 761 psi.

Twenty-five pressure-fatigue cycles at the operating pressure were reached with another tank, even though liner creasing resulted in a leak during the last cycle. The design requirement was 25 cycles without failure.

Another tank met the design requirement of 30-day storage with N_2O_4 at 350 psi and 110°F.

SECTION III

DESIGN (TASK I)

A design and engineering drawings were prepared for a 12-in.-dia by approximately 36-in.-long, metal-lined, glass-filament-wound tank for the containment of N_2O_4, at 350 psi and 110°F, for a 30-day period. The material and dimensional parameters specified by the Air Force Materials Laboratory were considered, as was minimum practical weight, with special emphasis on provisions for an adequate margin of safety. The tank contained a 0.006-in-thick 347 SS liner bonded to an overwrap of S-901 glass-filament roving impregnated with a corrosion-resistant resin system.

1. COMPUTER STUDY

The design criteria for these tanks are summarized in Table I. The liner was to be approximately 12 in. in diameter and 30 in. from tangent to tangent (cylinder-to-end-closure junction).

With this information, a computer study was undertaken (using an analysis and formula developed by Aerojet under National Aeronautics and Space Administration Contract NAS 3-6292)[2] to obtain the coordinates of the head contours and other design features. The filament shell was investigated by means of a netting analysis, which assumed that the stresses were constant along the path of the filament and that the structural contribution of the resin matrix was negligible. A planar winding path was used for the longitudinal filaments. The filament-wound shell and metal shell were combined by equating strains in the meridional and hoop directions and adjusting their radii of curvature to match the combined strengths of the materials at the design pressure. The pressure-vessel heads were designed first, and the cylinder was designed to complement them.

The computer study established the optimum head contours at both ends of the vessel, the filament- and metal-shell stresses and strains at zero pressure and the design pressure, the hoop-wrap thickness required for the

---

[2]E. E. Morris, F. J. Darms, R. E. Landes, and J. W. Campbell, Parametric Study of Glass-Filament-Reinforced Metal Pressure Vessels, NASA CR 54-855, April 1966.

TABLE I

DESIGN CRITERIA

Aerojet Drawing No.	178028
Internal volume, cu in.	3967.0
Outside diameter, in.	12.102
Operating pressure (p_o), psi	350
Proof pressure (p_p), psi	385
Design single-cycle burst pressure (p_b), psi*	761
Fatigue life, cycles	25 to p_o
Service life, days	30
Maximum temperature, °F	+110
Minimum temperature, °F	---
Enclosed propellant	N_2O_4

*Failure will occur in the hoop filaments.

TABLE II

DIMENSIONAL AND MATERIAL PARAMETERS

Aerojet Drawing No.	178028
Internal volume, cu in.	3967.0
Outside diameter, in.	12.102
Inside diameter of heads, in.	12.000
Inside diameter of cylinder, in.	12.012
Liner thickness, in.	0.006
Total composite-wall thickness, in.	0.028
Longitudinal	0.010
Hoop	0.018
Boss-to-boss length, in.	38.68
Length from boss base to boss base, in.	37.34
Forward-boss outside diameter, in.	2.37
Aft-boss outside diameter, in.	2.37
Liner and boss material	347 SS
Glass filaments	S-901 (formerly S-994)
Roving type	12-end
Resin matrix	RS-11 (pre-impregnated)
Liner-to-composite adhesive	Narmco 7343/7139

cylindrical portion, and the weights, volumes and filament-path lengths for the components and the complete vessel. The dimensional and material parameters are shown in Table II.

2. TANK DESIGN

The head-contour coordinates established as above were used in the liner design (Figure 1). The data from the computer analysis were also used to design the tank assembly (Figure 2).

The optimum longitudinal-composite thickness was calculated to be 0.008 in. It was estimated that 20-end, S-901, preimpregnated, glass roving would produce a minimum composite thickness of 0.014 in., and that 12-end roving would yield a thickness of 0.010 to 0.012 in. Single-end roving would produce a thickness of 0.007 to 0.008 in., but the fabrication time and complexity would be significantly increased in comparison with multiple-end roving. The 12-end roving was selected to assure an adequate margin of safety and to comply with the recommendation of the vendor (U.S. Polymeric, Inc.) for roving-preimpregnation feasibility.

A design was also prepared for the head reinforcement (Figure 3) to be used around each polar boss (Figure 4). The basic criterion was a maximum allowable strain of 0.5% in the filaments in the head area. The angle used to lay up the tapes was calculated as described in Appendix I. A preliminary fatigue-cycling test indicated that excessive strain conditions were being encountered in the head area at the edge of the doily reinforcement. The tapes were therefore lengthened and the longer tapes were incorporated in the last tank. This design is shown in Figure 5.

3. DESIGN ANALYSIS

The tank design was analyzed to determine the stresses in the glass filaments under various loading conditions. The safety margins based on comparison of the single-cycle design-allowable filament strength with the filament stress produced at the design operating pressure of 350 psi were 1.18 for the hoop filaments and 1.70 for the longitudinal. Calculations based on the estimated strength remaining after a 30-day environmental test at the operating pressure yielded safety margins of 0.20 for the hoop filaments and 0.49 for the longitudinal. The tank was thus shown to have an adequate margin of safety for the 30-day sustained-pressurization test.

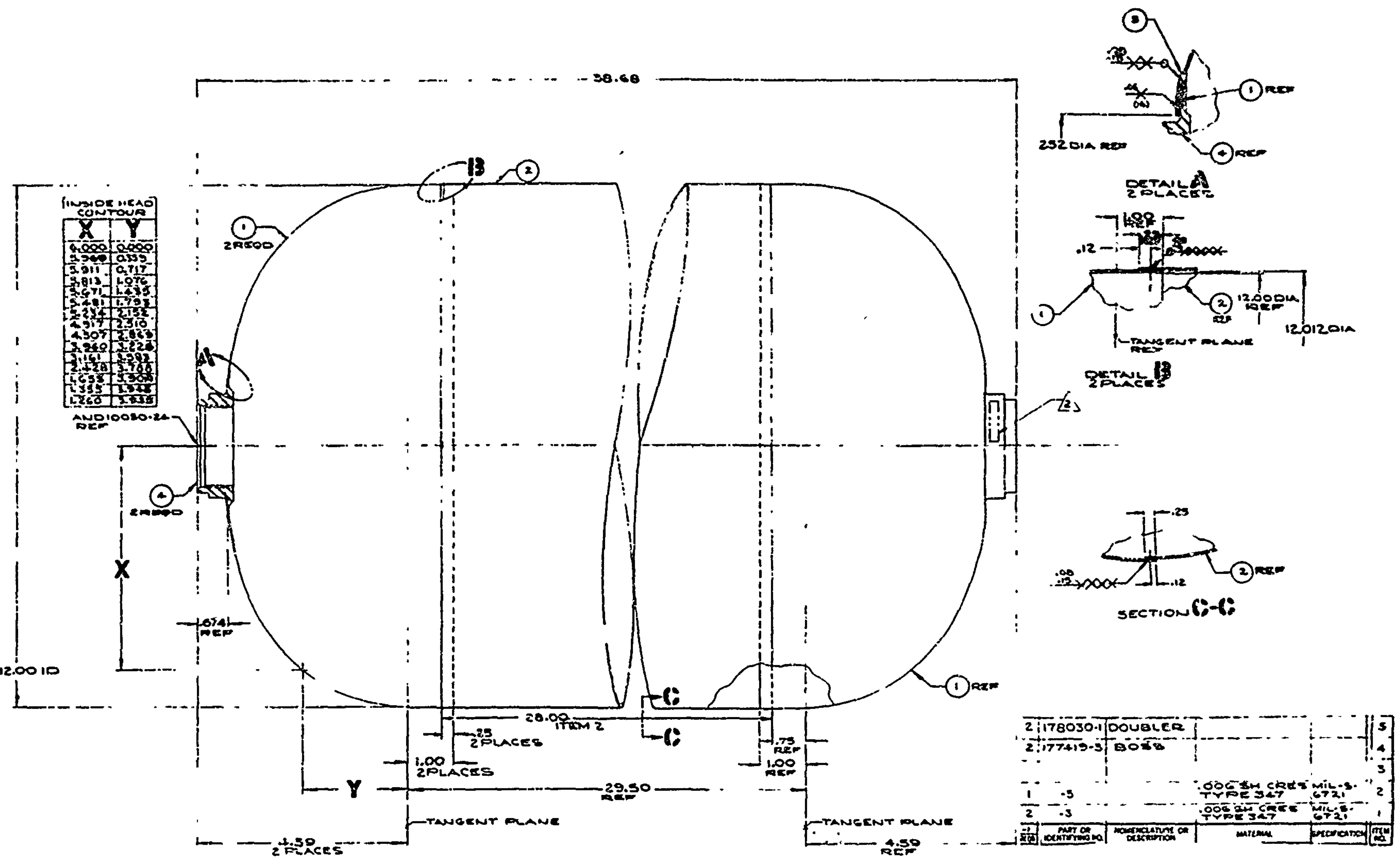
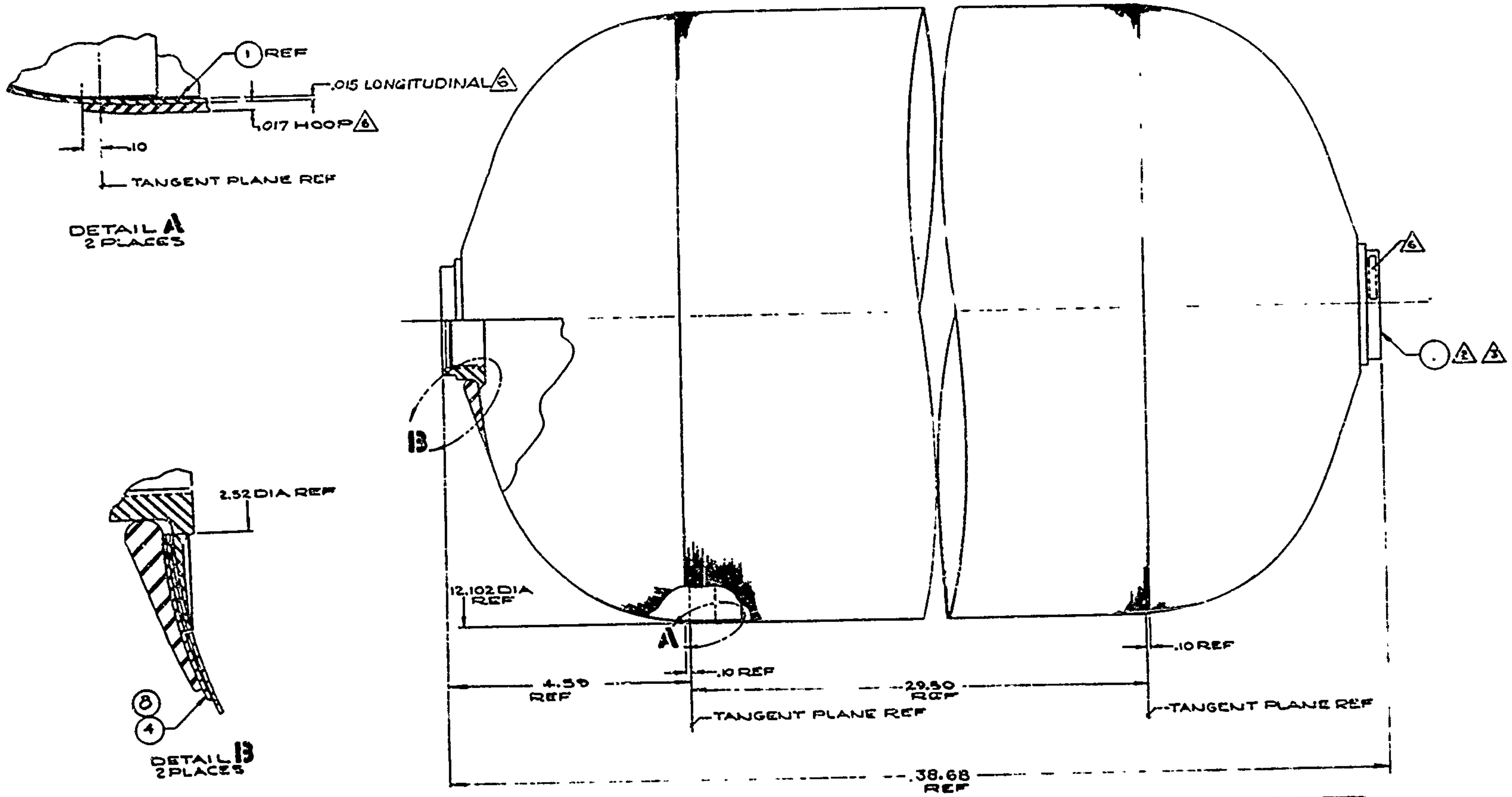


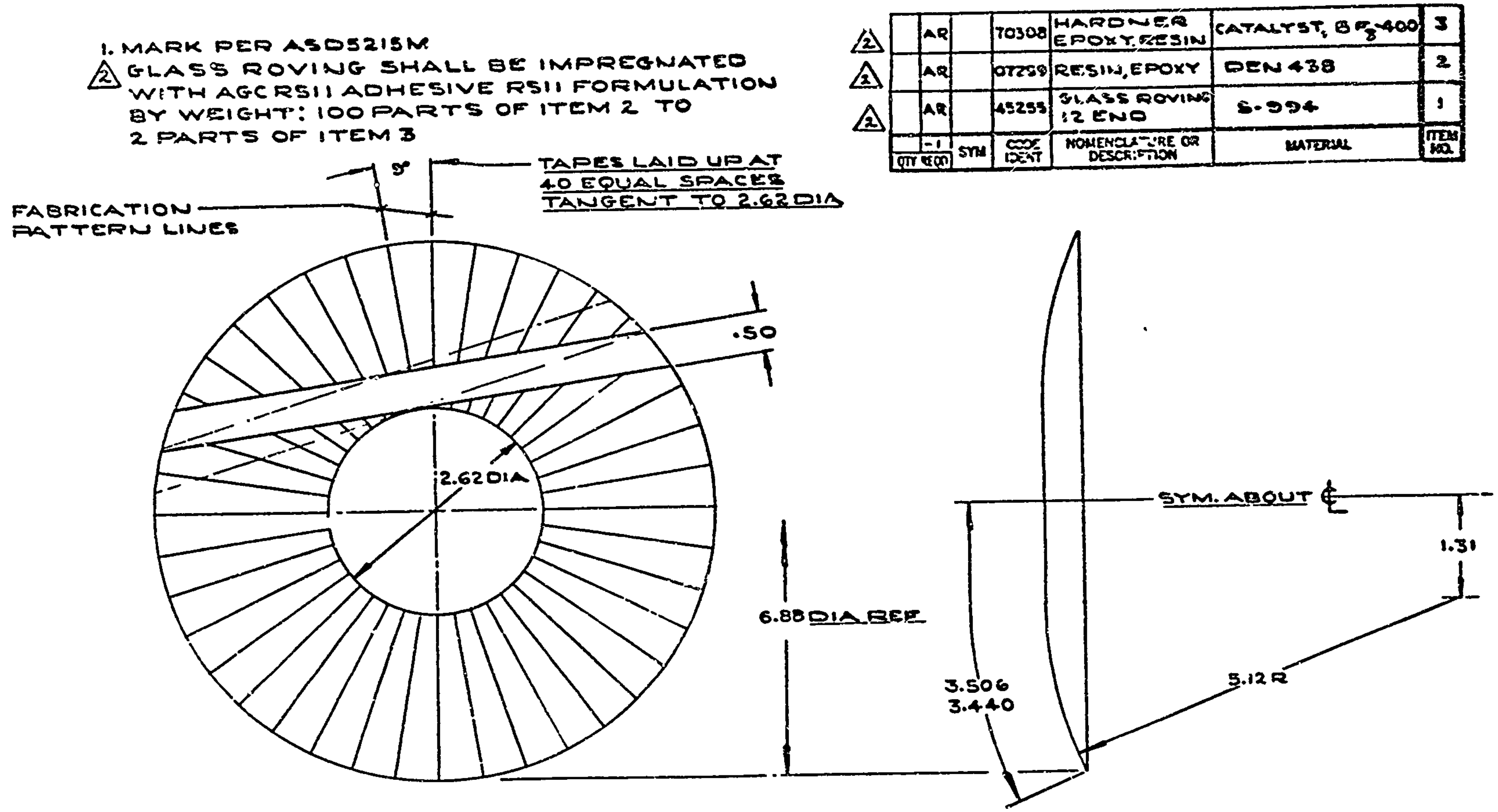
Figure 1. Liner Assembly, 12-in.-dia Tank (Dwg No. 178029)



NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. CLEAN CHAMBER LINER ASSY PER AGC-STD-1221.
3. PRIOR TO GLASS WINDING & ASSY OF ITEM 4 OR ITEM 8 COAT ITEM 1 WITH ITEM 5 & 6
4. GLASS ROVING SHALL BE IMPREGNATED WITH AGC RS11 ADHESIVE. RS11 FORMULATION BY WEIGHT: 100 PARTS OF ITEM 3 TO 2 PARTS OF ITEM 2.
5. WINDING TENSION: 3 LBS PER STRAND
6. WINDING PATTERN:
   LONGITUDINAL - 1 REVOLUTION, .015 INCHES THK 452 TURNS ± 1 TURN FOR TIE OFF, 12-END ROVING TAPE
   CIRCUMFERENTIAL - 3 LAYERS, .018 INCHES THK 470 TURNS PER LAYER IN 29.50 INCH LENGTH, 1 STRAND TAPE
7. CURING CYCLE OF GLASS RESIN COMPOSITE:
   2 HOURS AT 200°F
   2 HOURS AT 250°F
   8 HOURS AT 300°F

-3	-1	SYM	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	ITEM NO.
2				178158-1	REINFORCEMENT		8
AR	AR		45255		GLASS ROVING 12 END	S-994	7
AR	AR		04622		HARDENER EPOXY RESIN	CATALYST 7139	6
AR	AR		04622		RESIN, EPOXY	7343	5
	2			178C97-1	REINFORCEMENT		4
AR	AR		07259		RESIN, EPOXY	DEN 438	3
AR	AR		70304		HARDENER, EPOXY RESIN	CATALYST BF_3-400	2
1	1			178029-1	CHAMBER LINER ASSY		1

Figure 2. Tank Assembly (Dwg No. 178028)



2	AR		70308	HARDNER EPOXY RESIN	CATALYST, BF$_3$-400	3
2	AR		07259	RESIN, EPOXY	DEN 438	2
2	AR		45255	GLASS ROVING 12 END	S-994	1
	-1 QTY REQD	SYM	CODE IDENT	NOMENCLATURE OR DESCRIPTION	MATERIAL	ITEM NO.

Figure 3. Head Reinforcement, Initial (Dwg No. 178097)

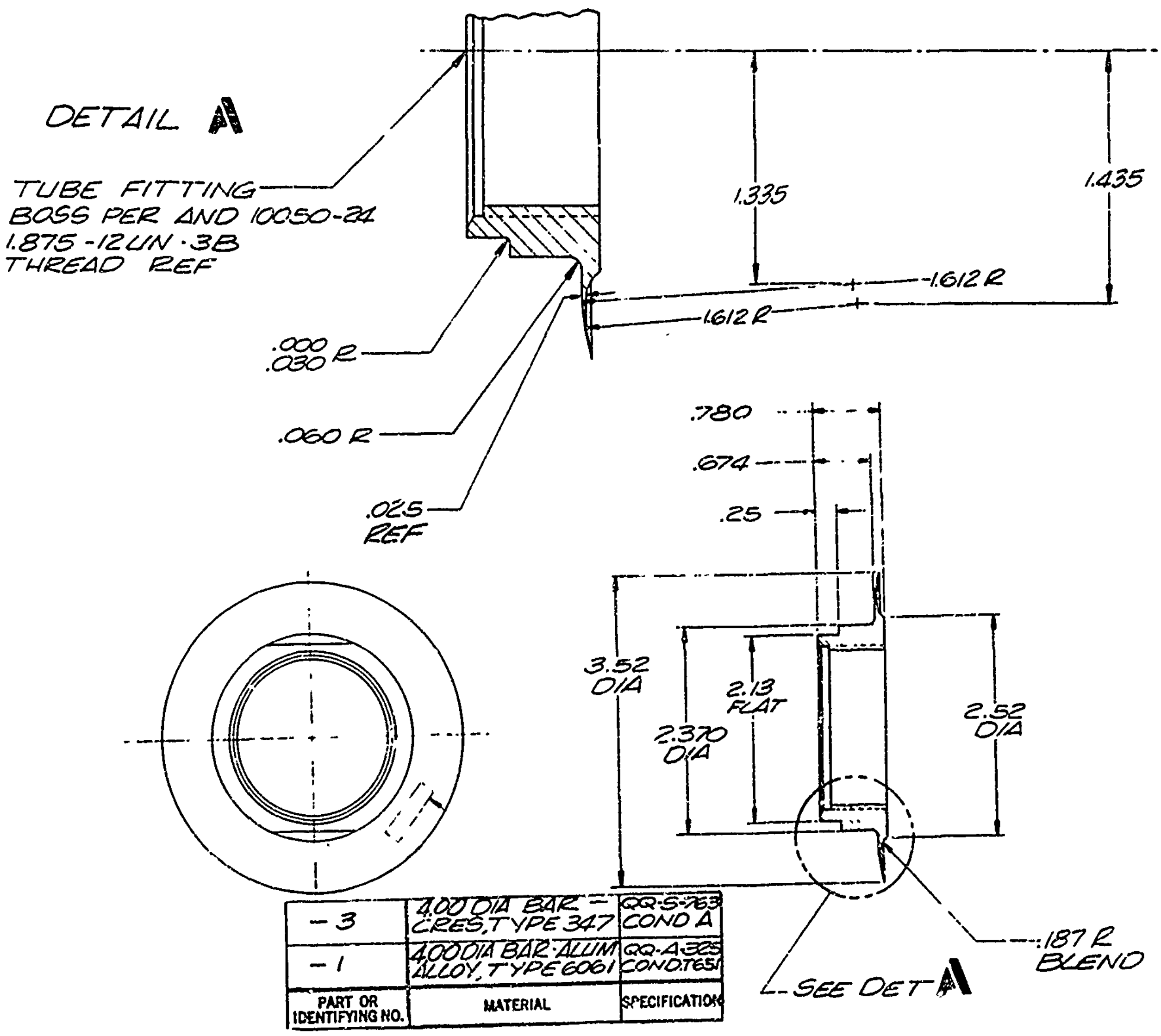


Figure 4. Polar Boss, 12-in.-dia Tank (Dwg No. 177419)

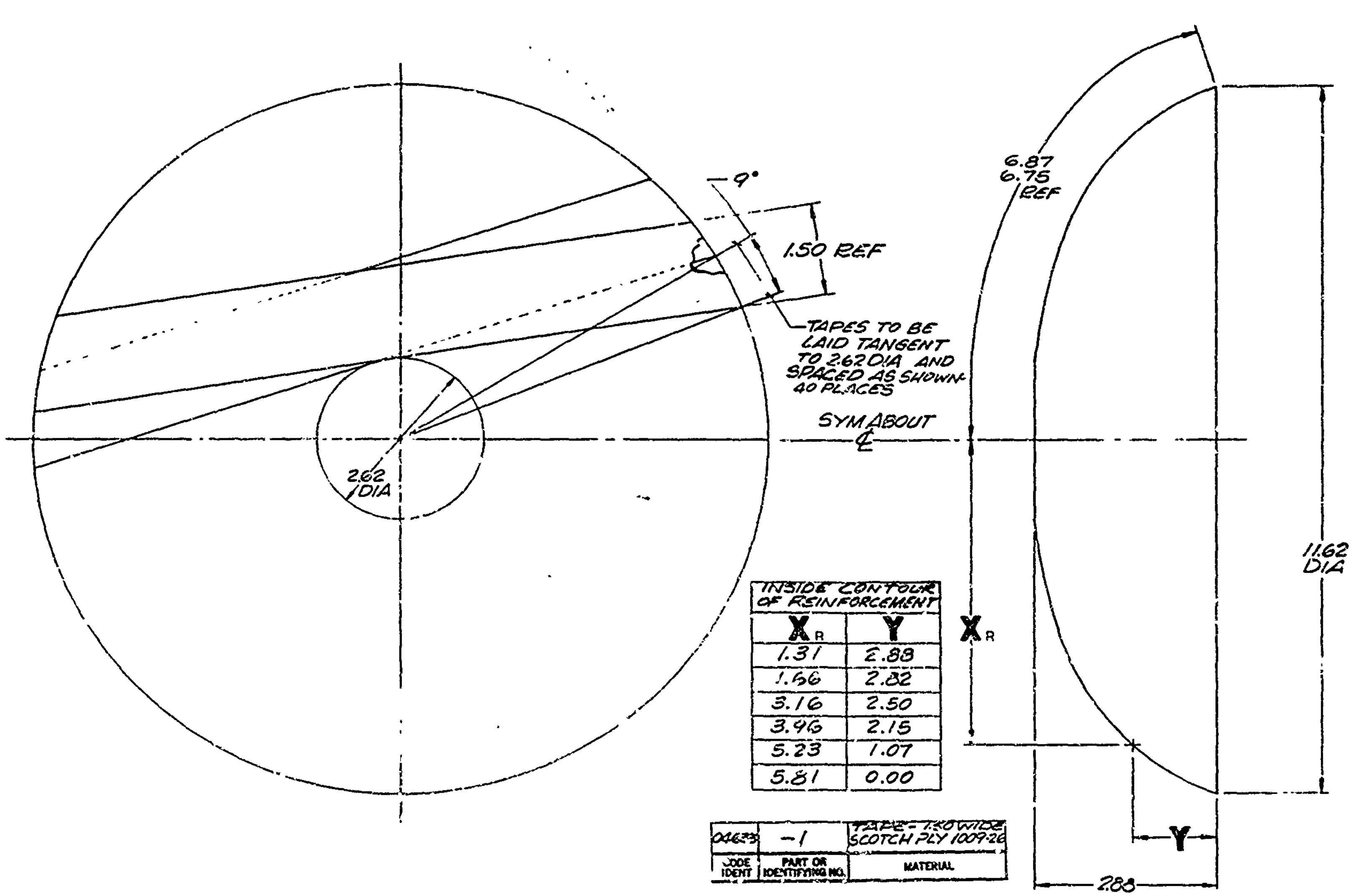


Figure 5. Head Reinforcement, Final (Dwg No. 178158)

The design burst pressure for the tank was 761 psi in the hoop filaments and 850 psi in the longitudinal. Appendix II presents the methods of calculation and the values for the design-allowable strengths.

4. WEIGHT ANALYSIS

The weights of the various components of the tank were calculated from the design details. They were based on mean values for the resin content in the preimpregnated roving and optimum composite thicknesses. A tabular summary is presented below.

		Estimated Weight, lb
Forward head		0.18
Aft head		0.18
Cylindrical section		1.90
Head reinforcements (2)		0.30
	Composite structure	2.56
Metal liner		2.58
Bosses (2)		0.90
	Metal hardware	3.48
Total		6.04

These weights are based on the ability of the tank to successfully withstand 25 cycles to the operating pressure and sustain a 30-day period at the operating pressure, with no margin of safety remaining after this service cycle.

SECTION IV

FABRICATION (TASK II)

Four, metal-lined, filament-wound tanks were fabricated using (a) materials and techniques developed under Contract AF 33(615)-1671, and (b) the design prepared in the work under Task I. The liners were made from 347 SS by pressure forming of the end domes, machining of the polar bosses, and roll-resistance seam welding of the segments. They were wound with S-glass roving impregnated with the RS-11 resin system used under Contract AF 33(615)-1671.

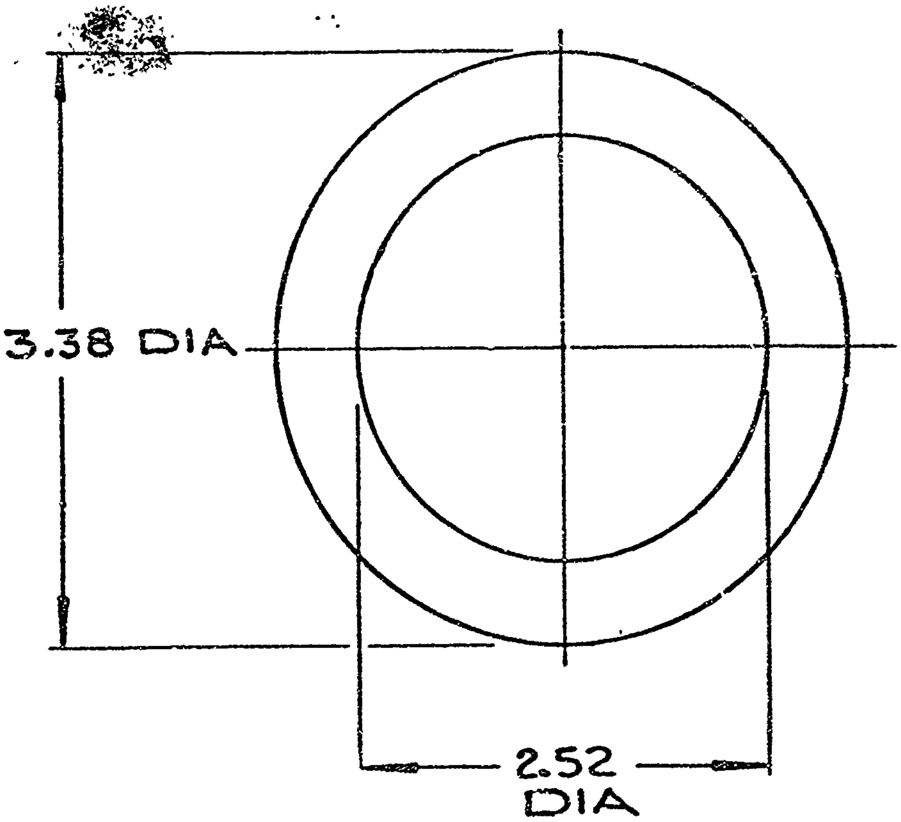
1. LINER

The head sections of the liner were fabricated by a pressure-forming process in which 0.006-in.-thick 347 SS foil was sandwiched between soft steel sheets and forced through a ring by a plug. They were then heat-treated to relieve stresses that had been introduced, were removed from the sandwich construction, were trimmed, and were punched for the boss opening.

The polar bosses were machined from 347 SS bar stock in accordance with the drawing shown in Figure 4. Particular care was taken to maintain the flange thickness. Welding doublers used in joining the head to the boss were fabricated from 0.008-in.-thick 347 SS foil in accordance with Figure 6. A slight radius was rolled into the doubler to provide close contact between the head section and the flange on the boss.

The cylindrical section of the liner was fabricated from 0.006-in.-thick 347 SS foil by roll-resistance seam welding two longitudinal sections together to the required diameters. Welding was necessary because the maximum width in which 347 SS foil is available is 24-1/2 in.

The liner parts were joined together by roll-resistance seam welding after being fixed in position by spot welding. The bosses were first welded to the head sections as shown in Figure 7. The doubler (Figure 6) was used over the metal of the head to ensure positioning within the thickness of the metal, and thus a gas-tight weld. The head sections were then joined to the cylindrical section with the aid of a curved electrode inserted through the boss opening.



-1	.008 SH CRES TYPE 347	MIL-S-6721
PART OR IDENTIFYING NO.	MATERIAL	SPECIFICATION

Figure 6. Welding Doubler, Boss (Dwg No. 178030)

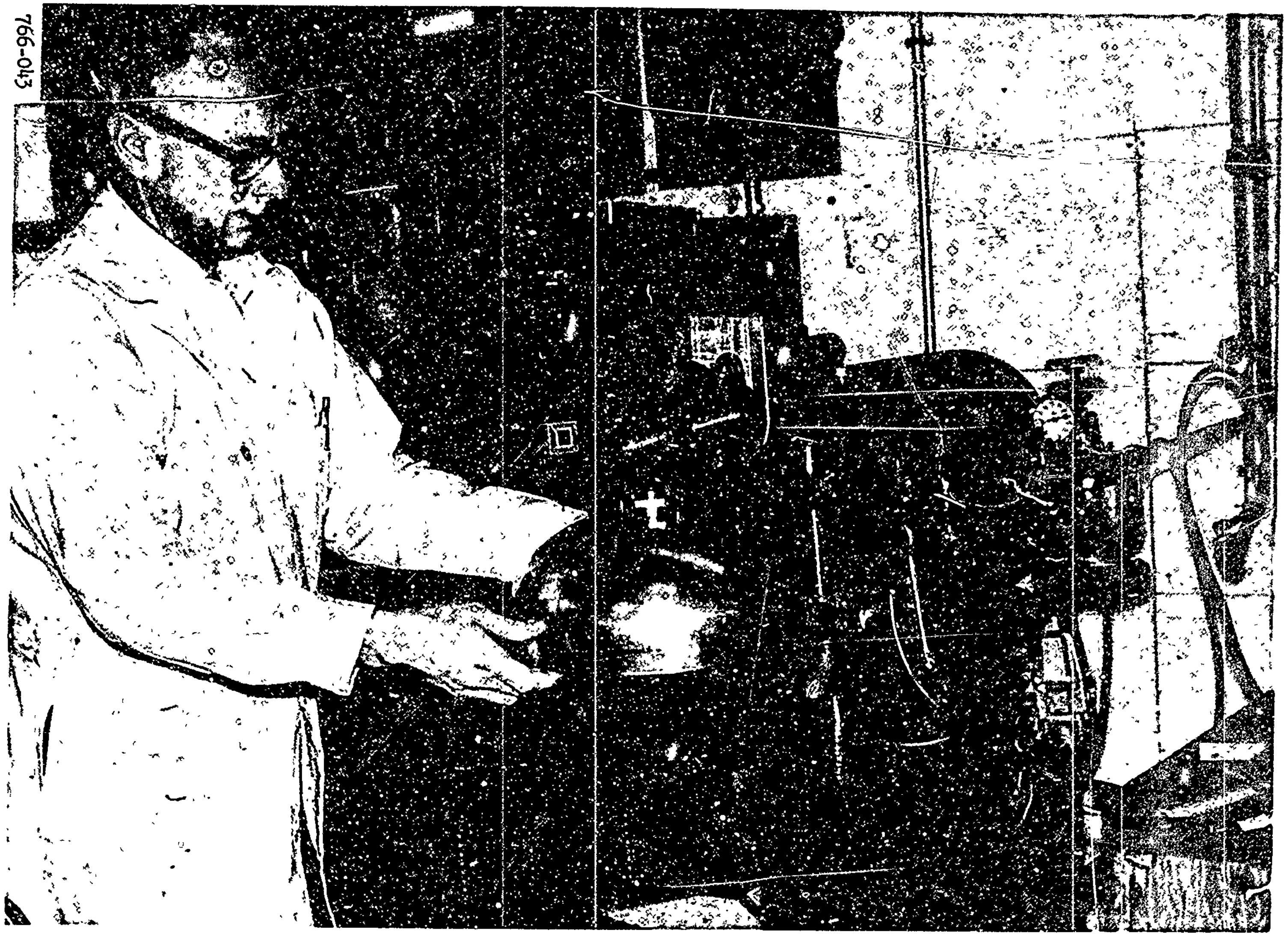


Figure 7. Tank Fabrication, Welding of Head Section to Boss

Two leak checks were made on each tank liner. The welder made a dye-penetrant test on each welded joint, and each liner was helium-leak-checked with a mass spectrometer under a pressure of 50 psi. All liners successfully passed these tests.

Internal liner reinforcement was provided by introducing a soluble plaster lining in liquid form through the boss openings. The plaster solidified quickly, and a stepwise operation was used to ensure a uniform lining approximately 1-1/2 to 2 in. thick. Figure 8 shows the tank liner after this operation. The liner and plaster were dried for 24 hours at 200°F to produce a rigid structure for filament winding.

The outsides of the tank liners were cleaned and etched according to Aerojet Standard AGC-STD-1221,[3] which involves preliminary cleaning in a strong alkaline solution at 180°F, followed by a 30-min dip at 200°F in a pickling solution that consists of 63.0 ±6.0% nitric acid and 0.4 ±0.001% hydrofluoric acid. This operation is illustrated in Figure 9. The tank liners were allowed to dry and were then enclosed in a polyethylene bag until they were prepared for filament winding.

2. TANK ASSEMBLY

The four propellant tanks were filament-wound according to standard Aerojet procedures. A rotating-arm-type machine was used for the longitudinal winding, and a horizontal-lathe-type machine for the hoop winding.

While the first tank liner was being set up, the threads on the winding shaft became galled and removal of the shaft from the stub shaft in the winding arm required a very high torque. Because the plaster mandrel inside the liner was slightly crushed during this operation, the liner was disconnected and an attempt was made to remove the plaster in the washout stand. Sudden failure of the fill line to the fixture, however, resulted in complete collapse and irreparable damage to the liner, which was replaced by a new liner from spare components at the welding vendor's plant.

---

[3] Method of Hot Nitric Acid Pickling, 5 November 1964.

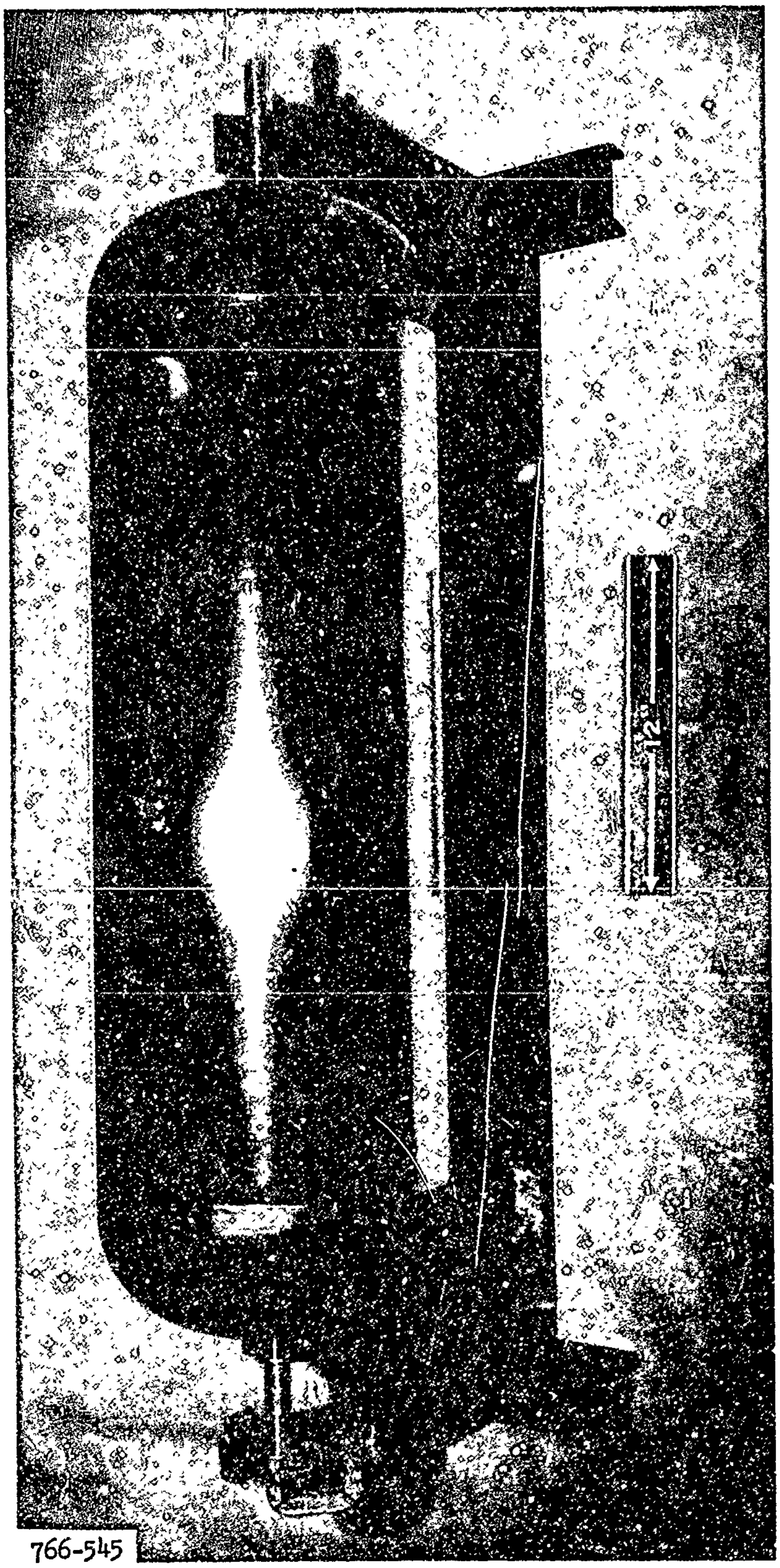


Figure 8. Tank Fabrication, Liner After Insertion of Plaster

Figure 9. Tank Fabrication, Cleaning of Liner

The second and succeeding liners were processed satisfactorily. The high length-to-diameter (L/D) ratio of the tank made alignment of glass roving from the payoff mechanism to the liner surface difficult, but the problem was solved by the addition of an extension to the winding shaft (Figure 10).

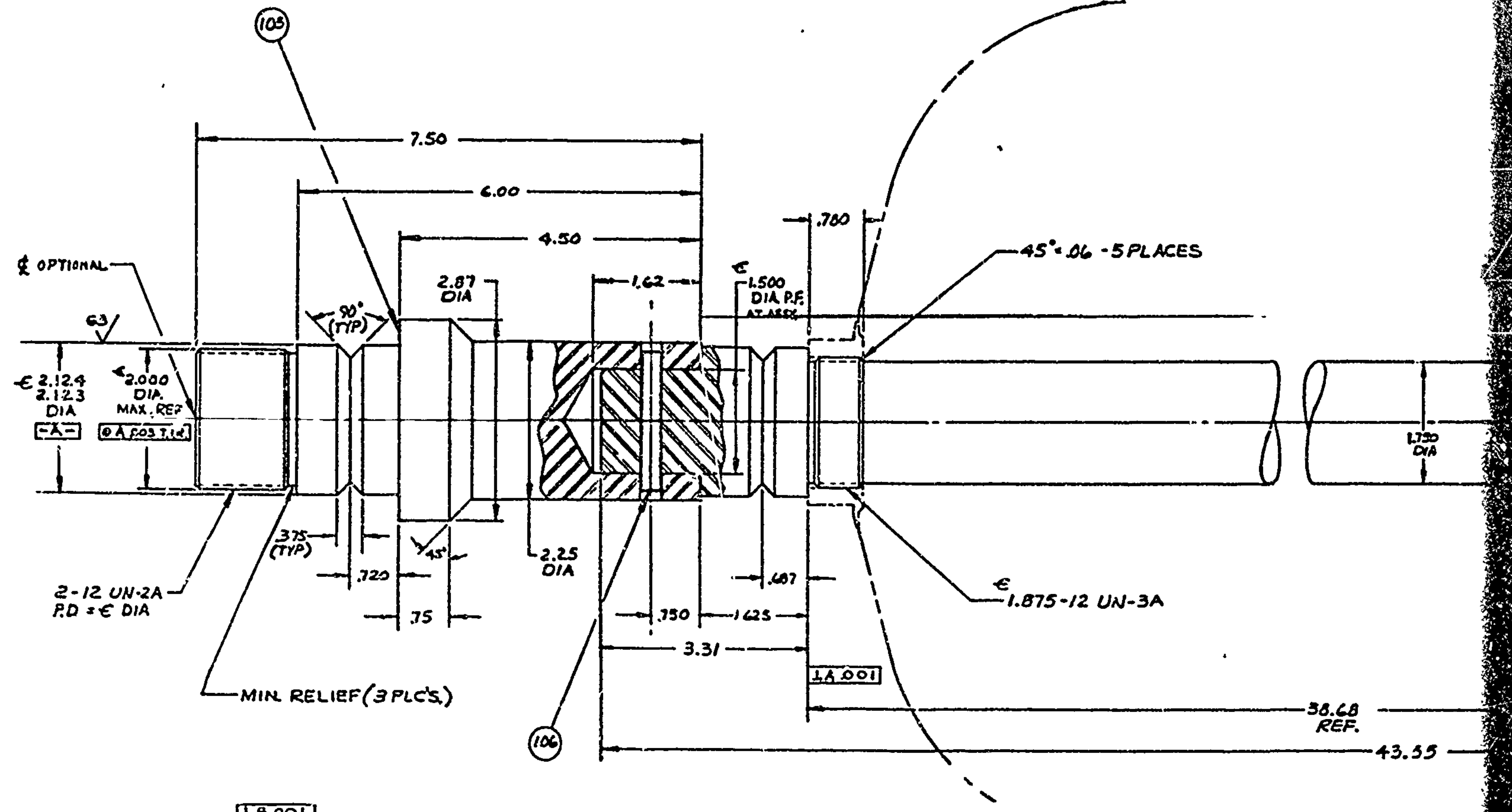
The preimpregnated-glass-roving tension was maintained by a magnetic brake device on which the spool of roving was mounted. The tension on the longitudinal roving was held at 2 lb for the first three tanks; it was estimated that this tension would increase to 2.5 to 3.0 lb at the tank liner surface. For the last tank, the payoff tension was increased to 3.0 lb to increase the pressure between the overwrap and the metal liner and thus obtain maximum adhesion. The tension on the hoop roving was maintained at 2.5 lb.

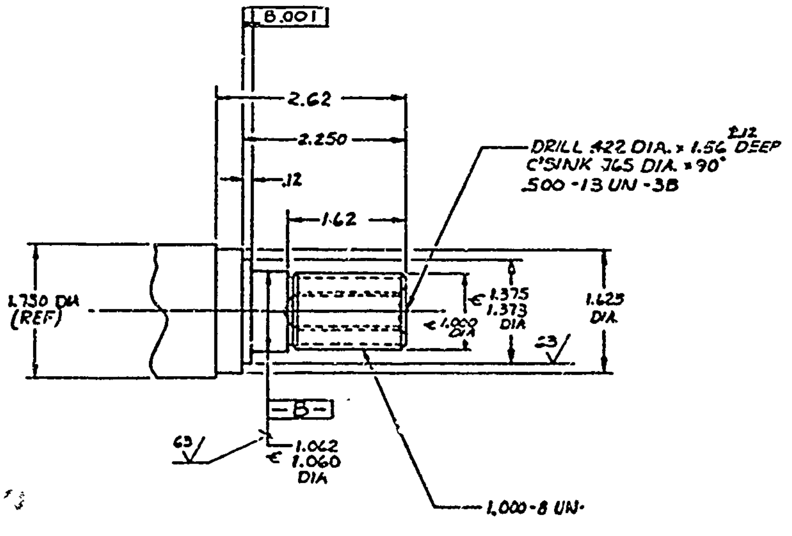
The winding shaft was inserted in the plaster-reinforced liner, and the winding mandrel and liner were attached to the stub shaft while the two parts were horizontal. The complete assembly was inserted into the winding arm of the filament-winding machine and was tightened in place.

The plastic bag covering the liner was removed for application of the adhesive: 100 parts by weight of Narmco 7343 resin and 11 parts of Narmco 7139 catalyst. The catalyst was heated to 250°F to facilitate mixing with the resin, and the mixture was thinned to brushing consistency with methyl ethyl ketone (MEK). The adhesive was brushed on the liner to a thickness of approximately 3 to 4 mils. It was necessary to air-cure the adhesive for 5 hours at room temperature to provide a tacky,nonflowing surface for the glass roving.

The head reinforcements for the first three tanks were fabricated from 1/2-in.-wide, 12-end, S-901, glass-roving tape preimpregnated with the RS-11 resin system. However, excessive creasing at the edge of the doily on one end of Tank 12-3 occurred during the fatigue-cycling test; the other head had been reinforced with a larger doily and was still smooth after the test. The head reinforcements for Tank 12-4 were therefore fabricated from 1-1/2-in.-wide "Scotchply" 1009-26C tapes that were extended over the crown of the head sections.

After the angle was adjusted on the winding mandrel to ensure a tight winding pattern, the two doily head reinforcements were pressed in place over the polar bosses. The gears for the longitudinal-winding machine had been selected to produce a closed layer of 12-end preimpregnated roving in one



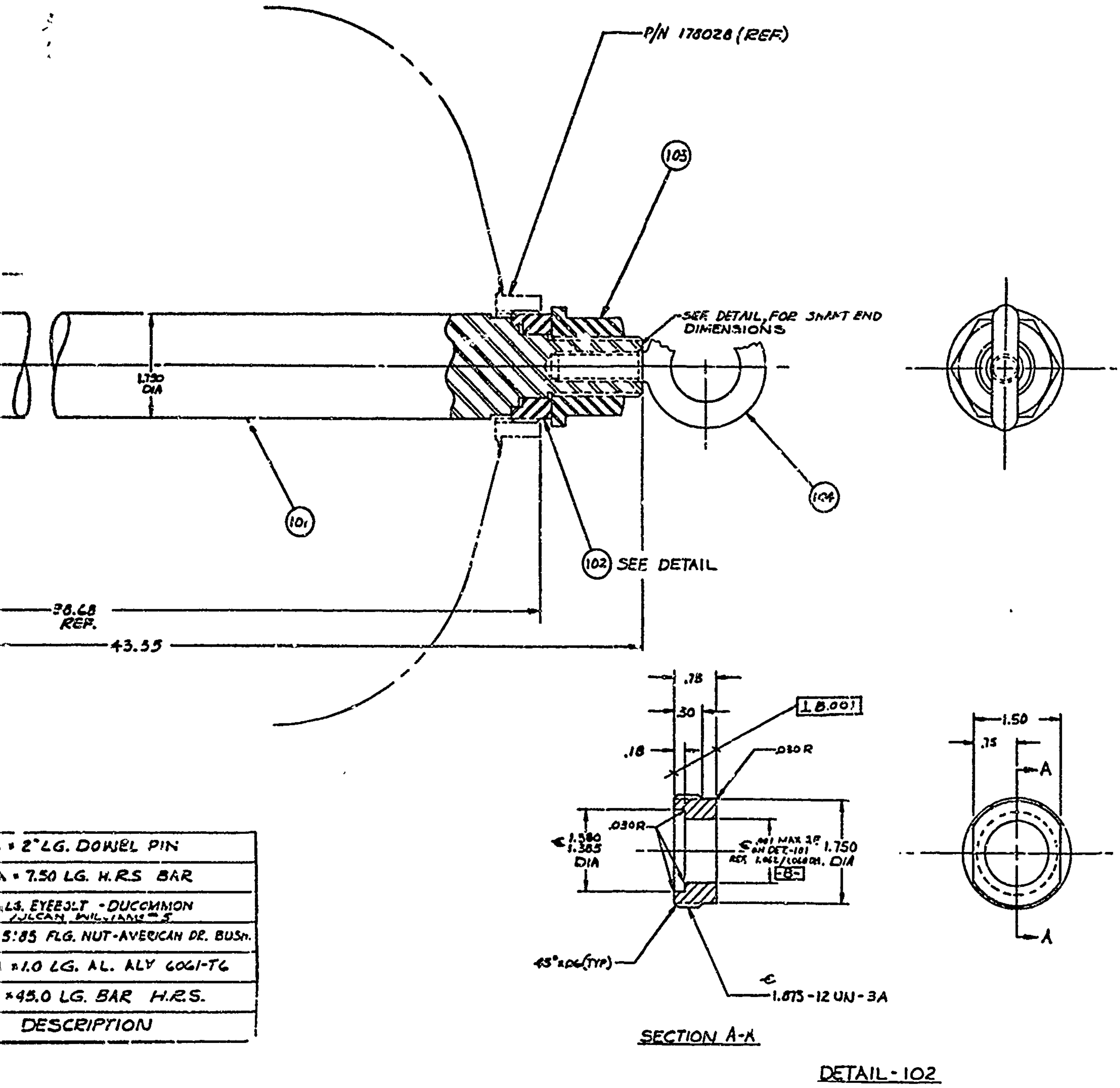


-101 SHAFT END DETAIL

106	1	5/16 O.D. × 2" LG. DOWEL PIN
105	1	3.0 DIA × 7.50 LG. H.R.S. BAR
104	1	½-13 × 1½ LG. EYEBOLT - DUCOMMON
103	1	ADB-25:85 FLG. NUT-AMERICAN DE
102	1	2.0 DIA × 1.0 LG. AL. ALY GOGI
101	1	2.50 DIA × 45.0 LG. BAR H.R.S.
DET. NO.	NO. REQ.	DESCEIPTION

Figure 10. Filament-Winding Shaft (Dwg

A



• 2" LG. DOWEL PIN
• 7.50 LG. H.R.S BAR
LS. EYEBOLT - DUCOMMON VULCAN WILLIAMS-5
5:85 FLG. NUT-AMERICAN DR. BUSH.
×1.0 LG. AL. ALY 6061-T6
×45.0 LG. BAR H.R.S.
DESCRIPTION

nding Shaft (Dwg No. T-120229)

B

revolution. The number of turns to accomplish this was calculated as 452. Figure 11 shows the start of the longitudinal-filament-winding operation. The tension on the glass roving was checked frequently. As soon as longitudinal winding was completed, the roving was tied off and the assembly was removed from the arm of the machine.

The tank liner and winding shaft were transferred to the horizontal-filament-winding machine. Gears had been installed to produce 470 turns of roving per pass of the 29.3-in. length of the cylindrical section, and the number of turns was checked before the roving was started. A tension of 2.5 lb produced a tight wrap that did not put the liner under excessive compression, and was therefore maintained for all tanks. Hoop winding is shown in Figure 12.

Tanks 12-1 through 12-4 had three layers of hoop winding at 470 turns per layer and a roving tension of 2.5 lb, with one revolution of longitudinal winding at 455 turns for Tanks 12-1 and 12-2 and 452 turns for Tanks 12-3 and 12-4, at a roving tension of 2 lb for the first three tanks and 3 lb for the fourth.

After filament winding was completed, the winding shaft was removed and replaced by a length of metal tubing to support the assembly and permit air circulation inside the tank during the cure. Curing was carried out in a circulating-type oven for 2 hours at 200°F, 2 hours at 250°F, and 8 hours at 300°F. After the cure, the plaster mandrel was washed out in a pump-actuated fixture with hot acetic-acid solution (200°F) made up of 60 vol% of water and 40 vol% of glacial acetic acid.

The weights of component parts, obtained during tank fabrication, are tabulated below for each tank (with the resin content shown parenthetically).

	Weight, lb			
	Tank 12-1 (23.7%)	Tank 12-2 (24.4%)	Tank 12-3 (24.2%)	Tank 12-4 (23.5%)
Longitudinal roving	1.26	1.25	1.22	1.26
Hoop roving	1.58	1.57	1.67	1.61
Bosses (2)	0.90	0.90	0.90	0.90
Liner	2.62	2.62	2.62	2.62
Head reinforcements (2)	0.27	0.27	0.49	0.81
Adhesive	0.20	0.20	0.20	0.20
Total	6.83	6.81	7.10	7.40

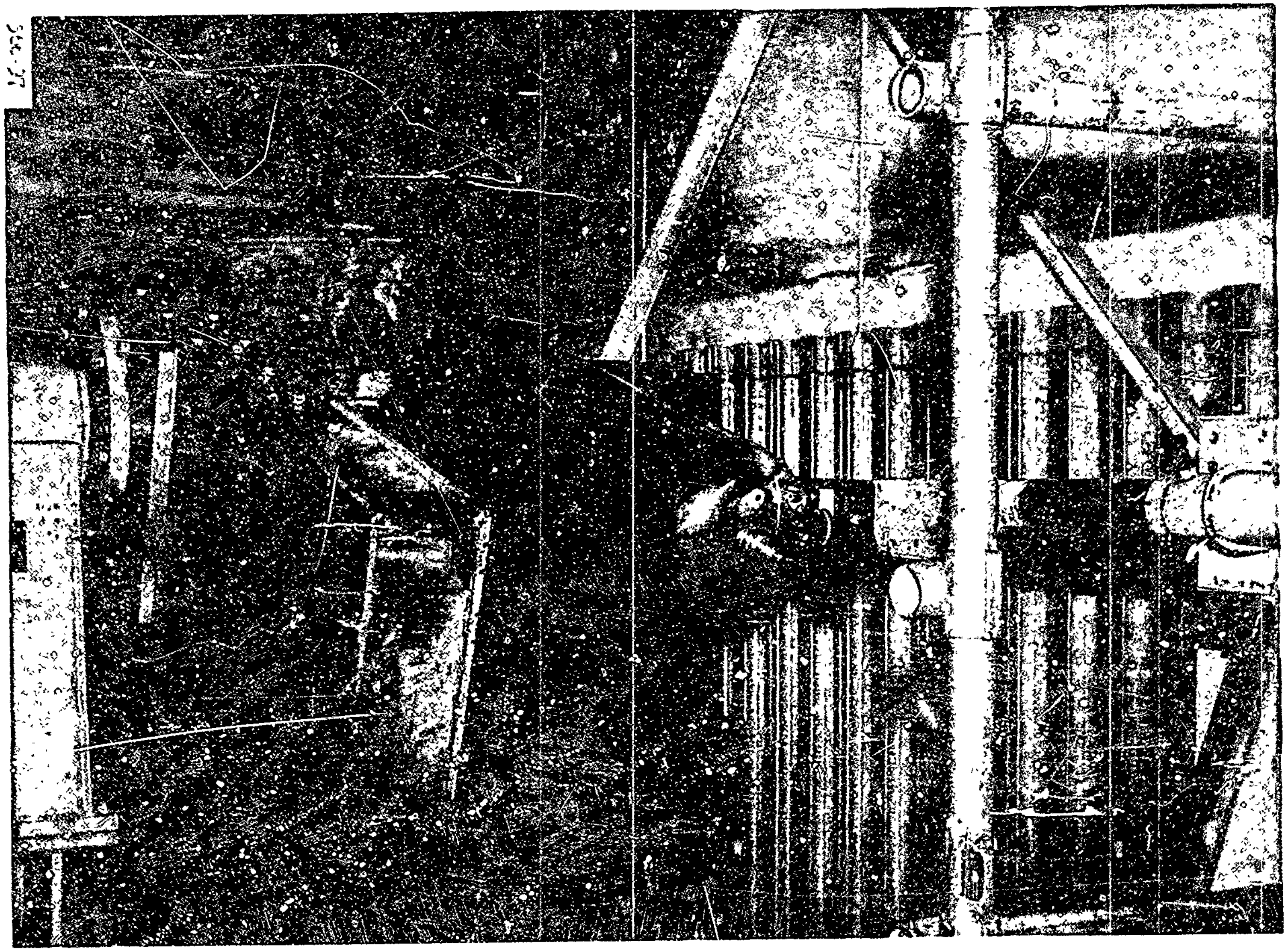


Figure 11. Tank Fabrication, Longitudinal Filament Winding

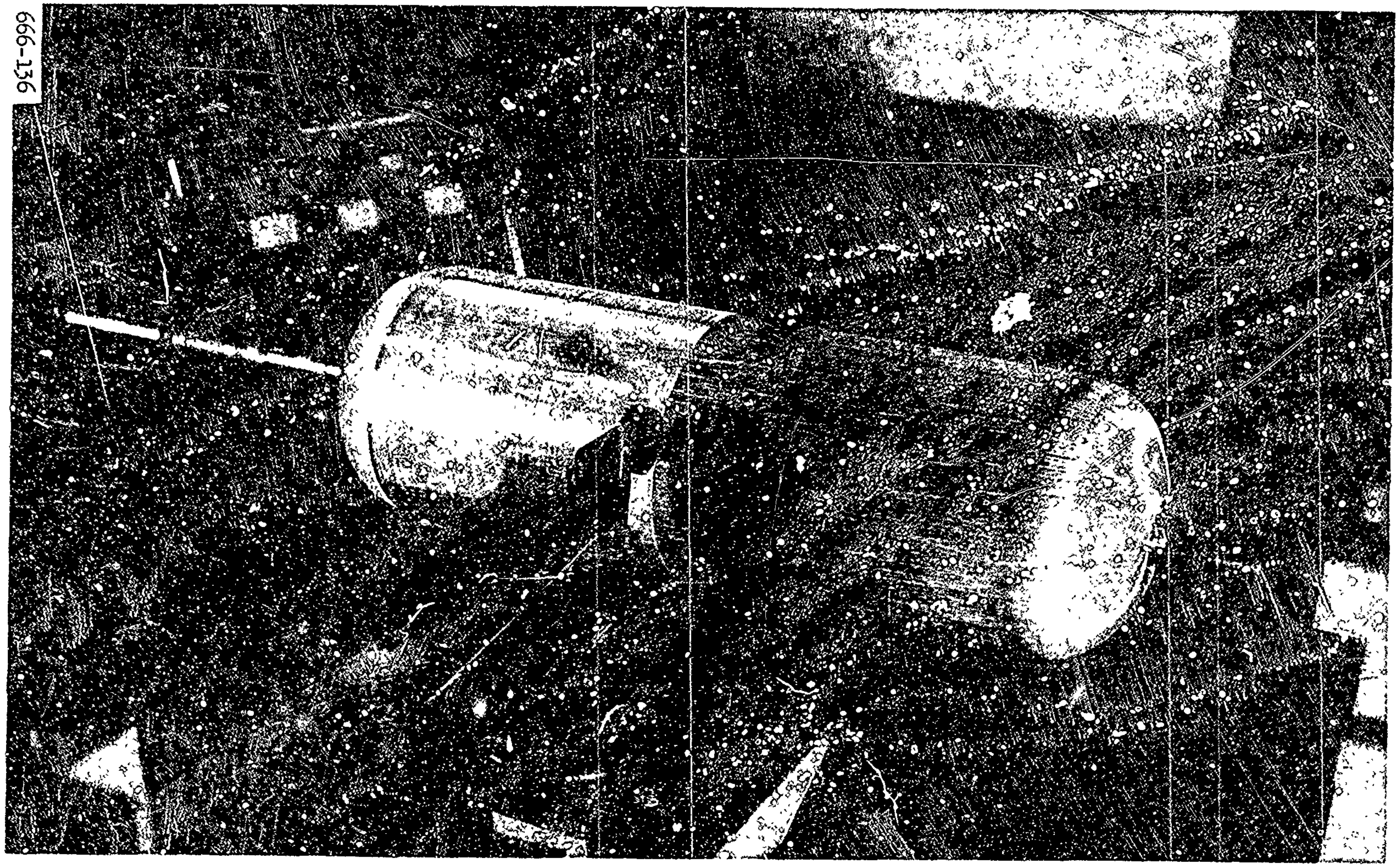


Figure 12. Tank Fabrication, Hoop Filament Winding

The actual weights were higher than the calculated weights for several reasons, among them the higher resin content of the roving, variations in metal-foil thickness, and heavier head reinforcements on Tanks 12-3 and 12-4.

SECTION V

TEST PROGRAM (TASK III)

In Task III the metal-lined, filament-wound tanks were tested to determine their ability to contain N_2O_4 at 100°F and a 350-psi pressure for 30 days. Hydroburst, fatigue-cycle, and N_2O_4-storage tests were conducted.

1. HYDROBURST

Tank 12-1 was hydroproofed to 385 psi and was helium-leak-tested at 50 psi with a mass spectrometer. It successfully passed the hydroproof test and held the pressure for 1 min. A slight gas leak was noted in the helium check, but the tank was used for the hydroburst test because it had held water pressure satisfactorily.

The tank was pressurized at 250 psi/min to the operating pressure of 350 psi, was held for 1 min, and was pressurized to the burst point. It failed in the hoop filaments at 750 psi (211% of the operating pressure and 193% of the proof pressure).

The design single-cycle burst pressure was calculated by methods described in the Aerojet Structural Materials Handbook[4] and covered in Appendix II. The burst pressure of 750 psi was 98.5% of the design single-cycle burst strength of 761 psi (see Table I).

Tank 12-1 had been instrumented with linear-motion transducers, as shown in Figure 13, to indicate longitudinal and hoop growth. Meaningful data interpretation was not possible, however, because of unexplained descrepancies in values obtained for longitudinal deflections. The readings on the hoop-growth linear-motion gages were also questionable, but the data were plotted (Figure 14) for the two gage locations (LM-3 and LM-4). At the burst pressure, the hoop strain was 2.4% at LM-3. The strain level at LM-4 (the top section of the tank) was 4.1% at 650 psi, at which point the readings went off the chart. The readings at LM-4, where the initial burst occurred, were erratic and are not considered meaningful. At the operating pressure of 350 psi, the hoop strain was 0.66% at LM-3 and 0.40% at LM-4.

---

[4]By E. E. Morris, W. T. Cox, F. J. Darms, et al., February 1964, Section 6.

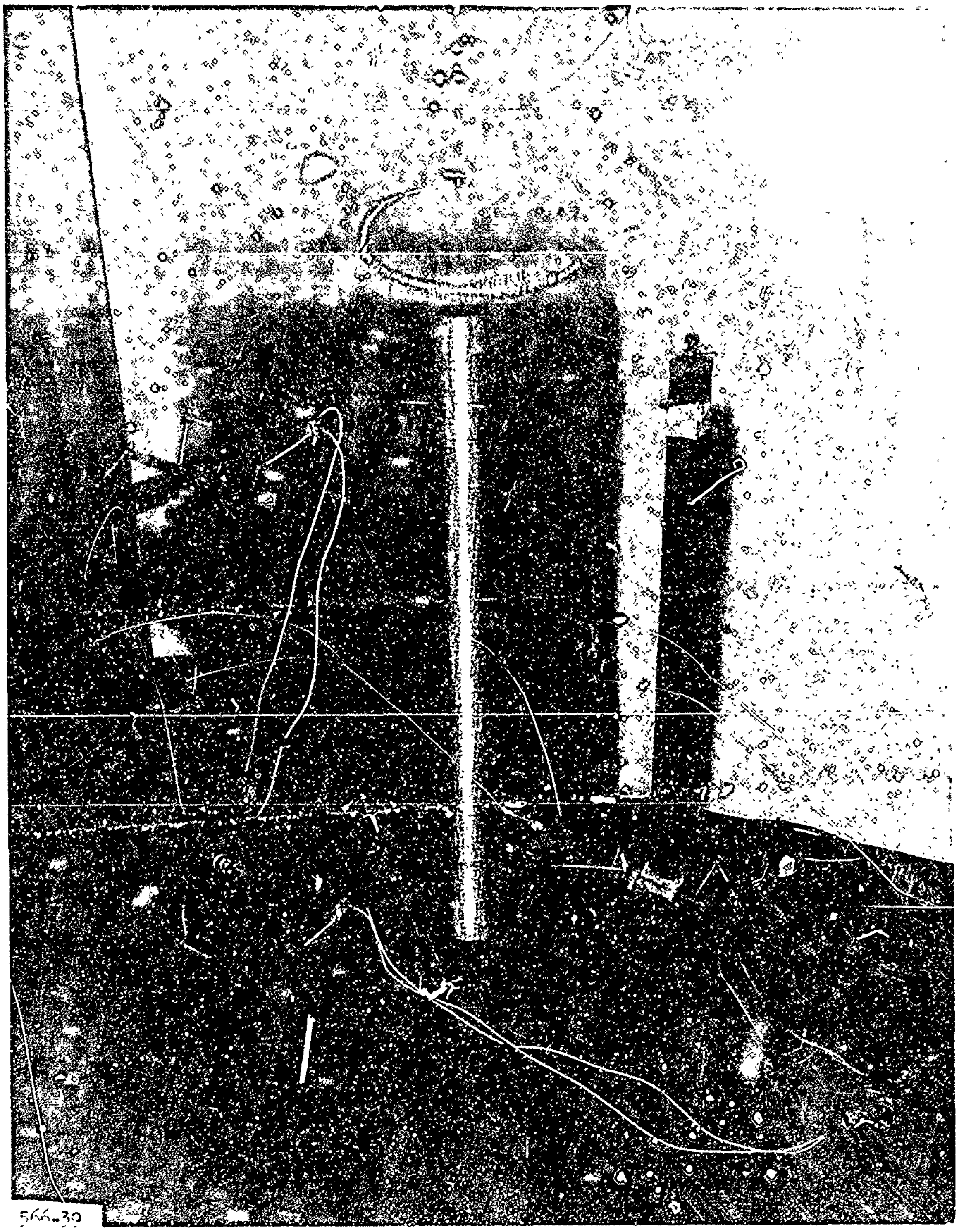


Figure 13. Instrumented Tank Before Hydroburst Test

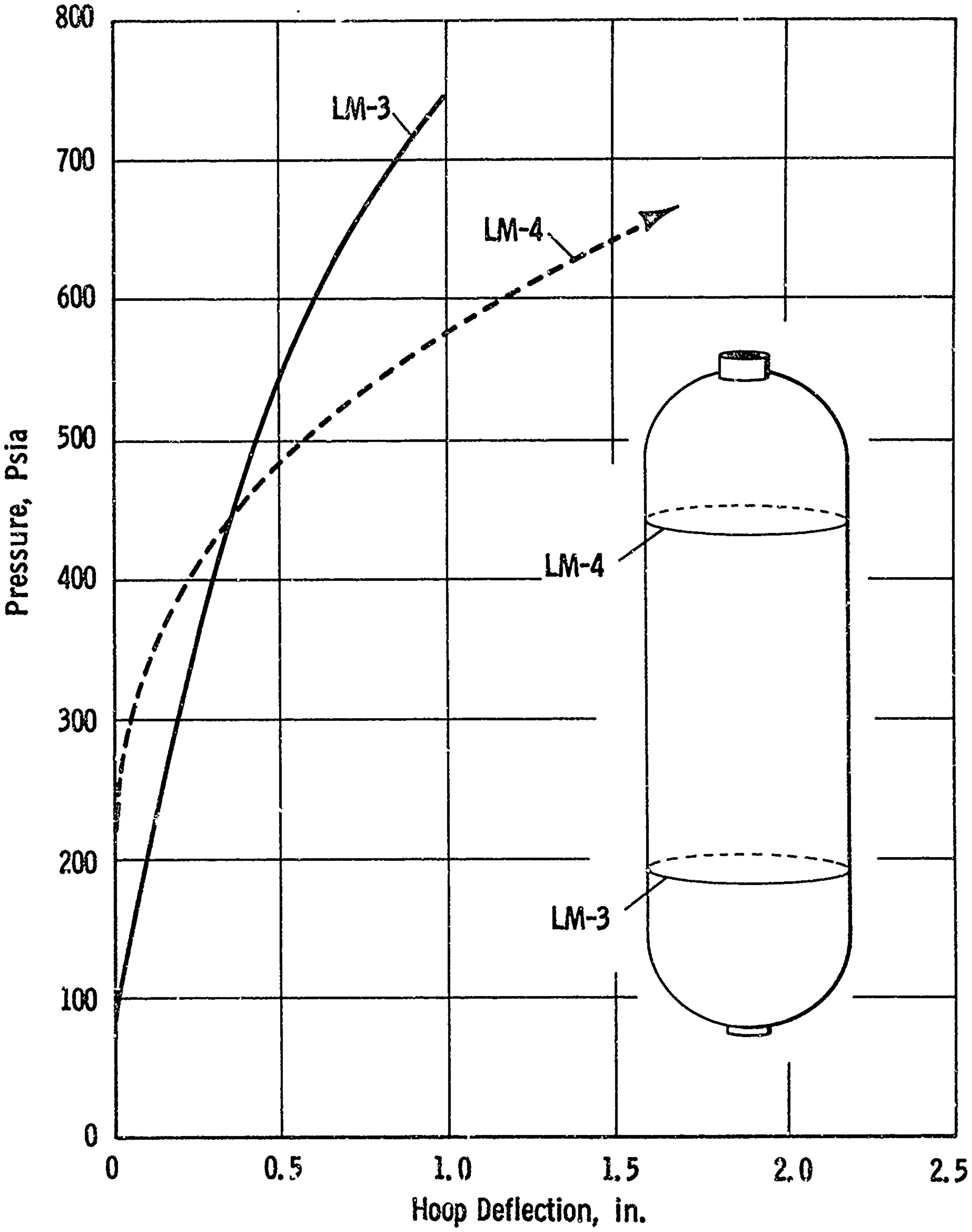


Figure 14. Tank 12-1, Pressure vs Hoop Deflection During Hydroburst

2. FATIGUE CYCLING

Tank 12-3 was hydroproofed to 385 psi, checked for leaks with the helium mass spectrometer, and fatigue-tested by pressurization from 0 to 350 psi at 250 psi/min. It developed a leak at the 11th cycle and would no longer hold pressure. Examination of the interior showed severe creasing at the edge of the doily reinforcement in the head section; the leak appeared near this area.

Another tank liner was fabricated from spare bosses and head sections that had been purchased with the initial order for the four tank liners. Enlarged head reinforcements were used on Tank 12-4 to reduce the creasing, the thickness of the adhesive film was increased somewhat by reducing the MEK dilution, and the longitudinal-filament tension was increased to 3 lb to increase the pressure on the adhesive bond between the liner and the overwrap.

Tank 12-4 was mounted horizontally to assure no restriction on end-to-end growth, and was instrumented to show longitudinal and hoop deflection. It was hydroproofed to 385 psi and fatigue-cycled for 25 times from 0 to 350 psi. During the last cycle, a small leak occurred at one end of the hoop area but did not interfere with pressurization. Examination of the interior revealed considerable liner creasing in the cylindrical section where the leak had occurred. The adhesive bond in this area was obviously not sufficiently strong to prevent separation from the filament-wound overwrap. The liner in the head sections where the larger doily reinforcements were used was not creased.

Fatigue-cycling data for Tank 12-4 are shown in Table III as longitudinal deflection vs pressure and hoop strain vs pressure. The longitudinal measurements were made between the polar bosses, and are shown as end-to-end deflections. The hoop measurements represented growth in the cylindrical area and are shown as percentages of hoop strain. The maximum longitudinal deflection was 0.365 in. and the maximum hoop strain was 0.816%.

The test data are shown as hysteresis-loop curves in Figures 15 and 16 for the 1st, 10th, and 24th cycles. The recording paper was expended on the venting of the 25th fatigue cycle, and data from the 24th cycle were used in the plots. A significant feature of the curves is a change in the rate of longitudinal deflection and hoop strain during the loading phase. On the longitudinal-deflection curve, the rate change starts at approximately 170 psi for the first cycle and continues at progressively lower pressures for

TABLE III

TANK 12-4, PRESSURE VS LONGITUDINAL DEFLECTION AND HOOP STRAIN

Pressure psi	1st Cycle	5th Cycle	10th Cycle	15th Cycle	24th Cycle	25th Cycle
			Longitudinal Deflection, in. - Loading			
0	0	0.080	0.100	0.090	0.075	0.055
50	0	0.100	0.110	0.125	0.100	0.110
100	0.030	0.120	0.140	0.145	0.143	0.145
150	0.065	0.160	0.185	0.175	0.170	0.170
200	0.160	0.200	0.210	0.215	0.205	0.188
250	0.230	0.240	0.250	0.250	0.250	0.235
300	0.280	0.290	0.290	0.290	0.290	0.280
350	0.365	0.350	0.355	0.350	0.340	0.320
			Longitudinal Deflection, in. - Venting			
300	0.355	0.350	0.355	0.340	0.340	---
250	0.345	0.340	0.340	0.330	0.325	---
200	0.315	0.315	0.320	0.320	0.305	---
150	0.270	0.270	0.280	0.275	0.277	---
100	0.232	0.240	0.237	0.242	0.225	---
50	0.180	0.185	0.180	0.205	0.167	---
0	0.070	0.093	0.085	0.070	0.100	---
			Hoop Strain $\left[(\Delta L)(100)/38.0\right]$, % - Loading			
0	0	0.121	0.121	0.105	0.092	0.078
50	0	0.158	0.132	0.105	0.121	0.078
100	0.079	0.210	0.205	0.205	0.205	0.205
150	0.205	0.290	0.290	0.290	0.330	0.316
200	0.329	0.355	0.369	0.369	0.410	0.410
250	0.473	0.500	0.500	0.510	0.527	0.527
300	0.618	0.618	0.618	0.618	0.658	0.658
350	0.790	0.790	0.790	0.790	0.816	0.816
			Hoop Strain $\left[(\Delta L)(100)/38.0\right]$, % - Venting			
300	0.777	0.777	0.777	0.777	0.777	---
250	0.738	0.738	0.738	0.738	0.738	---
200	0.658	0.658	0.658	0.658	0.658	---
150	0.552	0.552	0.552	0.580	0.552	---
100	0.410	0.422	0.410	0.410	0.410	---
50	0.263	0.290	0.290	0.290	0.284	---
0	0.105	0.132	0.121	0.092	0.121	---

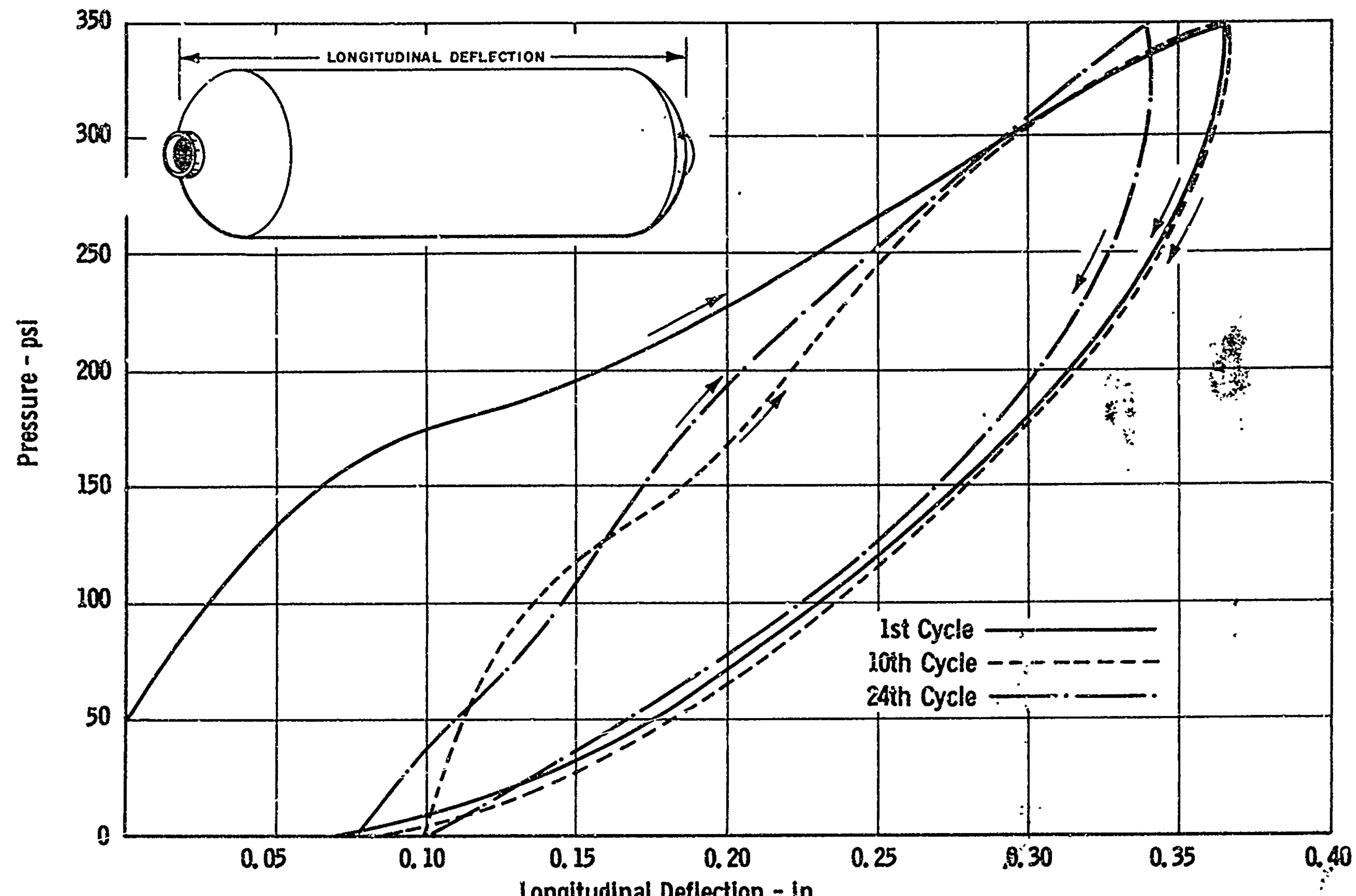


Figure 15. Tank 12-4, Pressure vs Longitudinal Deflection During Fatigue Cycling

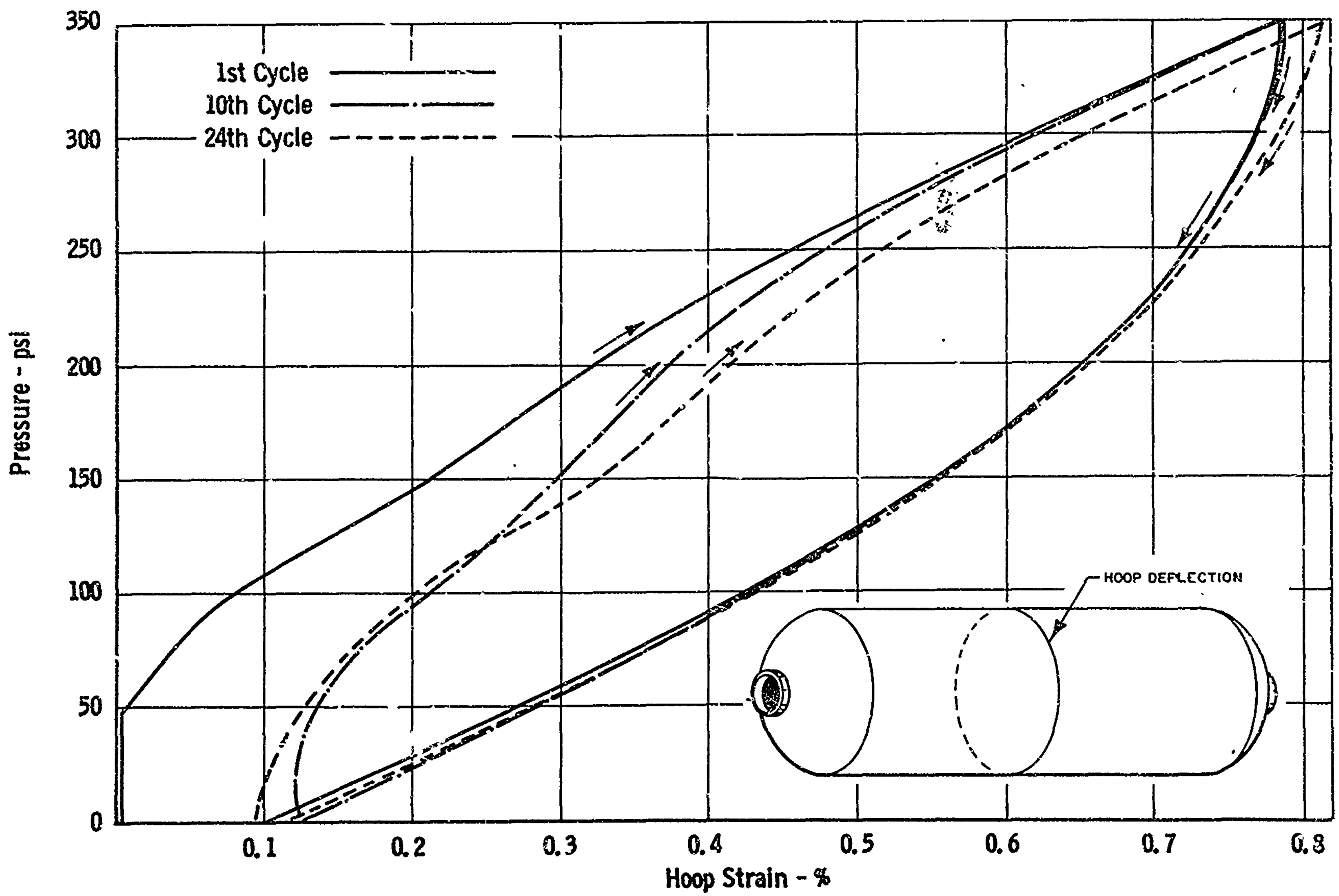


Figure 16. Tank 12-4, Pressure vs Hoop Strain During Fatigue Cycling

succeeding cycles. On the hoop-strain curve, the rate change starts at approximately 120 psi and continues at slightly lower pressures for succeeding cycles.

This characteristic deflection-and-strain-rate change is interpreted as meaning that the liner carries part of the pressure load during the initial phase of pressurization. The liner then goes past its yield strength, plastically deforms, and does not carry additional load. After a short period, the glass filaments take up the increasing load and the rate of deflection increases. The longitudinal-deflection and hoop-strain curves followed the same general pattern for all cycles, indicating that the liner was carrying part of the load during the initial stages of pressurization.

The shape of the curve for the venting or return phase was approximately the same for all cycles. After the 1st cycle, when most of the set in the longitudinal and hoop directions occurred, very little change in the final point of return was observed. This indicates that the glass-filament overwrap forced the liner into compression and the filaments themselves were not fatigued by the pressure cycling.

It is believed that the improved strength of the bond between the liner and the overwrap achieved in Tank 12-4 was a major factor in the increased fatigue-cycle life as compared with Tank 12-3. Theoretically, a complete bond between the liner and the case would distribute the strain level uniformly over the interior of the tank. Under these ideal conditions, the fatigue-cycle life of a smooth-bonded, metal-lined, filament-wound tank should reach a very high level.

3. N_2O_4 STORAGE

Tank 12-2 was hydroproofed to 385 psi, leak-tested at 50 psi with the helium mass spectrometer, and half-filled with N_2O_4. It was pressurized to 350 psi and was successfully held at this constant pressure for 30 days at 110°F.

The tank was decontaminated after the test. Examination of the liner showed no evidence of corrosion, although some creasing had occurred during hydroproofing, pressurization, and venting.

SECTION VI

CONCLUSIONS

Analysis of the design prepared for the fabrication of 12-in.-dia by 38.68-in.-long, metal-lined, filament-wound tanks showed an adequate margin of safety for the intended mission and minimum weight.

Fabrication procedures, adaptable to production operations, that were developed and used for the four test tanks yielded gas-tight liners to exact drawing dimensions. Minor fabrication problems in the filament-winding operation were satisfactorily resolved without major delay.

Satisfactory results were obtained in hydroburst testing. The target of 25 fatigue-pressure cycles (0 to 350 psia) was reached with one tank, although liner creasing resulted in a minor leak during the last cycle. A successful 30-day-storage test with N_2O_4 at the operating pressure and temperature demonstrated the dependability of a stainless-steel-lined, filament-wound tank for long-term storage of rocket propellants.

This work established the feasibility of fabricating stainless-steel-foil-lined, filament-wound tanks 12 in. in diameter by 38.68 in. long. The fabrication techniques could also be used for larger-diameter tankage, the only limitation being the availability of forming equipment for large head sections. Of particular significance is the ability to produce gas-tight liners from 0.006-in.-thick 347 SS foil by roll-resistance seam welding; this technique was proved successful in joining three layers of the foil together at seam joints in the cylindrical section.

The program also demonstrated that the fabrication methods produced tankage of satisfactory dependability for the required 30 days of N_2O_4 storage at a 350-psi operating pressure. An improvement in the adhesive bond between the metal liner and the filament-wound overwrap is indicated, however, for extensive fatigue cycling. An improved bond increased the measured fatigue life, and additional work should further extend the utility of the smooth-bonded, metal-liner concept.

SECTION VII

RECOMMENDATIONS FOR FUTURE WORK

It is recommended that the technology developed for metal-lined, filament-wound tankage in this and the preceding program be applied to scaled-up prototype structures for storable propellants to provide substantial weight savings.

In small filament-wound tanks such as those fabricated under this contract, the 0.006-in.-thick metal liner represents a major part of the total weight. In larger tanks the liner weight is a smaller fraction of the total, and weight-saving advantages of metal-lined, filament-wound tanks can be realized.

The relative performances of various types of filament-wound tanks were analyzed and compared with all-metal tankage in a recent study performed at Aerojet and reported in NASA CR 54-855.[5] The study revealed that the most satisfactory method of judging the efficiency of all-metal, filament-wound, and metal-lined filament-wound tanks is one that incorporates all the basic pressure-vessel parameters in a performance factor, pV/W, where p is the design pressure in pounds per square inch (and may be the operating pressure, p_o, or the burst pressure, p_b), V is the internal volume in cubic inches, and W is the pressure-vessel weight in pounds. The performance of filament-wound pressure vessels, assumed to be made from S-901-glass filaments, was determined for comparison with the performances of metal-lined filament-wound and homogeneous metal tanks. The assumed operating-pressure and filament-stress levels were similar to those used in the present program: 350 psi and a filament stress of about 200,000 psi at the operating pressure and $75^{\circ}F$. Performance factors were determined for filament-wound vessels without liners, as well as for vessels with 0.060-in.-thick elastomeric liners, 0.006-in.-thick stainless steel liners, and 0.006-in.-thick aluminum liners.

---

[5] _Op. cit._

The study showed that the performance of a vessel with a thin liner is directly proportional to the relative thicknesses of the filament winding and liner. In turn, for a fixed liner thickness, the relative thicknesses of the liner and filament winding are proportional to the tank design pressure and diameter; tanks with higher pressures and larger diameters will have higher performance.

This effect is shown in Figure 17,[6] which plots the operating-pressure performance factor, $p_o V/W$, against the major diameter of the tank for a constant operating pressure (350 psi) and tank diameters varying from 5 to 100 in. The figure reveals that a metal-lined, filament-wound, cylindrical tank with L/D = 3.0 has a much higher performance factor than a metal-lined, filament-wound, oblate spheroid of the same diameter; vessel performance increases significantly as tank diameter increases.

Figure 18 was prepared to indicate the relative performances of cylindrical and spherical, homogeneous metal tanks, filament-wound tanks, and metal-lined filament-wound tanks; the performance factors for the all-metal tanks were computed with the metal strength levels shown below.

		psi at 75°F		
Material	Condition	Ultimate Strength	Operating Stress Level	Density lb/in.
6Al-4V titanium alloy	Solution-treated and aged (STA)	165,000	110,000	0.162
5Al-2.5Sn titanium alloy	Annealed	140,000	93,500	0.162
2219 aluminum alloy	T87	65,000	43,300	0.102
301 SS	Full hard	200,000	133,000	0.286

The operating stress level was taken as the ultimate strength divided by 1.50.

The figure shows that filament-wound vessels with 0.006-in.-thick stainless steel liners (p_o = 350 psi and filament stress level = 200,000 psi) offer substantial weight savings over homogeneous metal tanks if the tank diameter is sufficiently large. As an example, a cylindrical, 28-in.-dia filament-wound tank with a 0.006-in.-thick liner has a performance factor equal to that for a heat-treated 6Al-4V titanium sphere; as the tank diameter

[6]Reproducing Figure 61 of NASA CR 54-855.

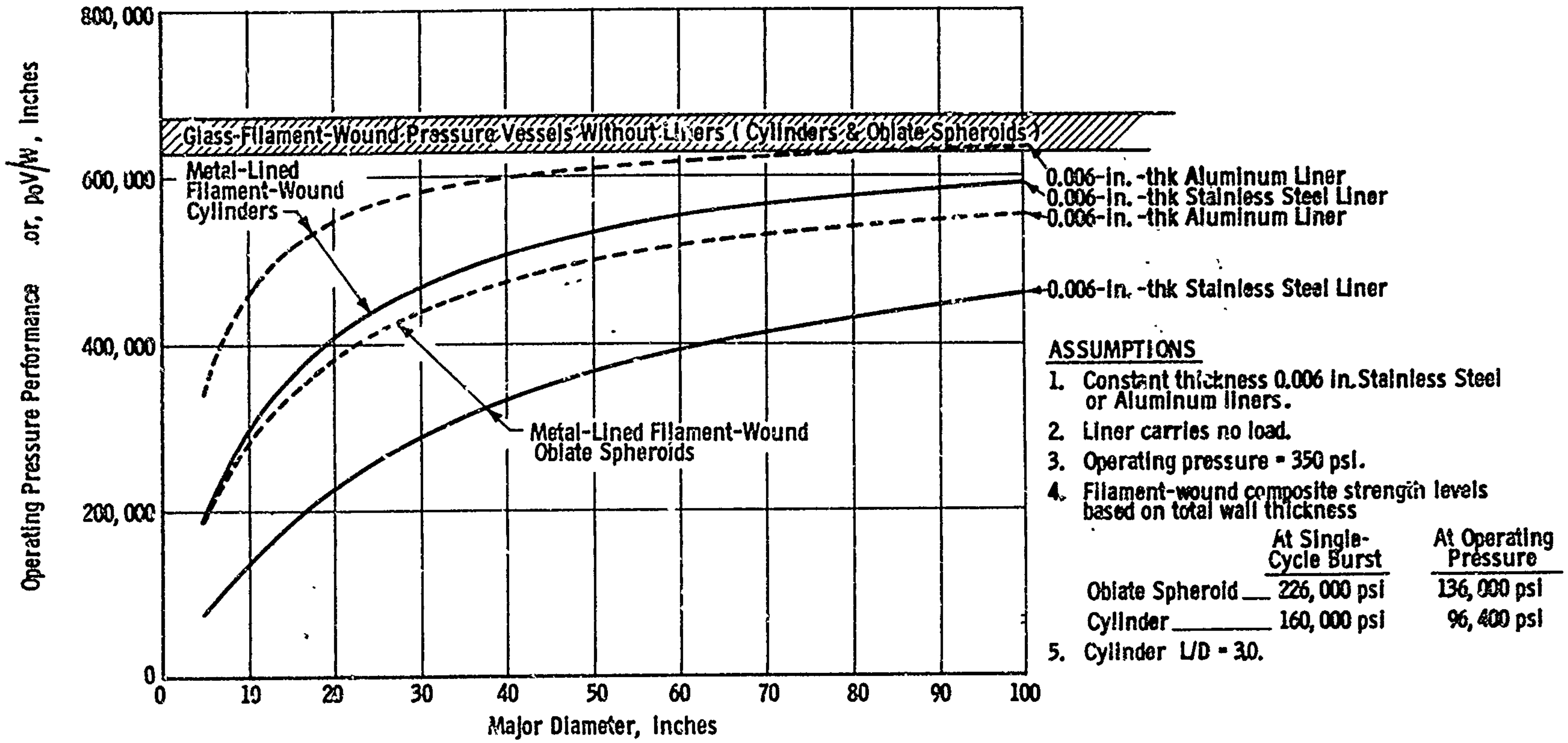


Figure 17. Operating-Pressure Performance
Metal-Lined Glass-Filament-Wound Tankage

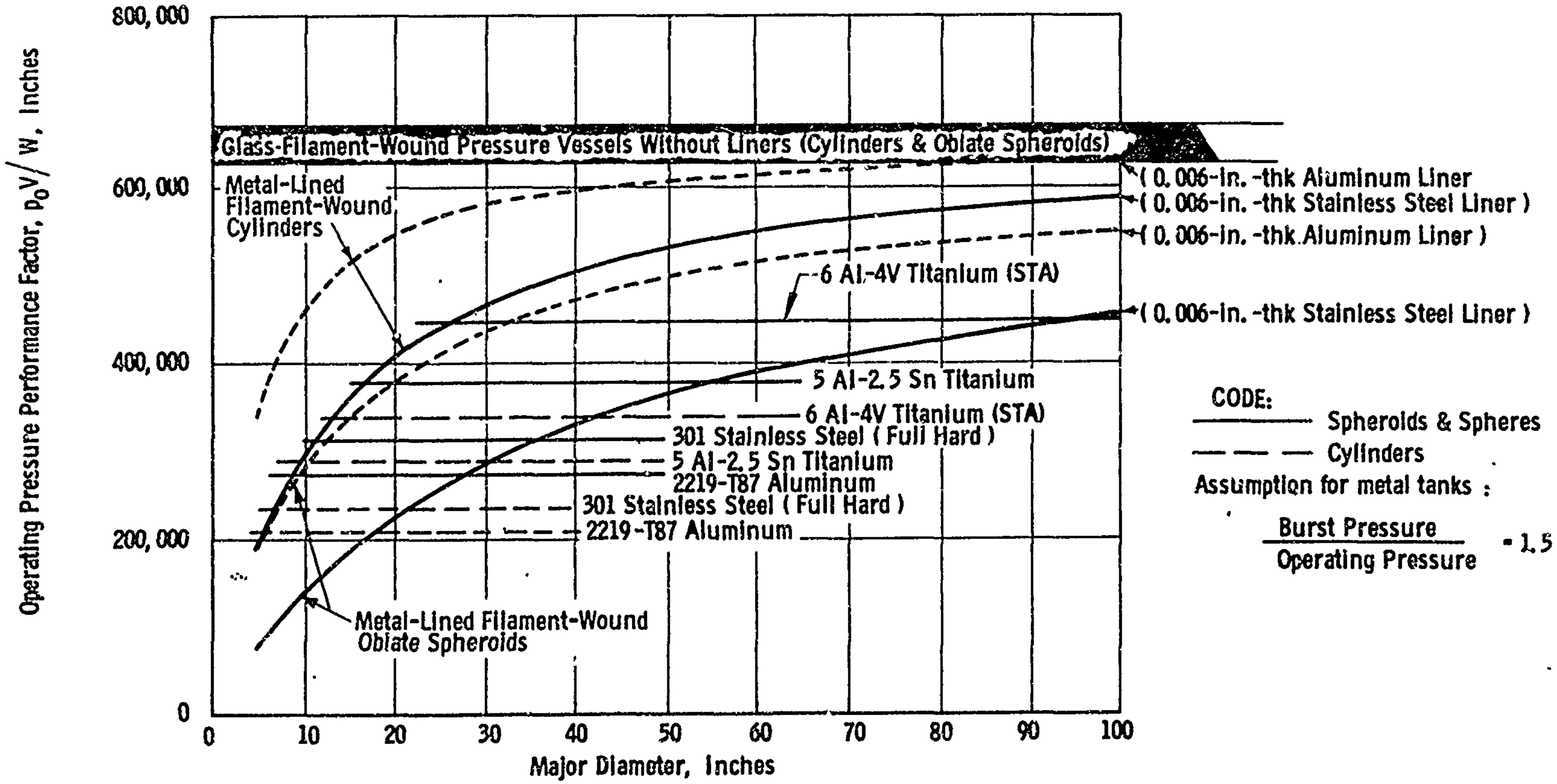


Figure 18. Operating-Pressure Performance
Metal Tanks vs Metal-Lined Filament-Wound Tanks

increases, so does the performance advantage of the metal-lined, filament-wound tank. Thus, major weight savings are attainable with low-pressure, filament-wound tankage.

The size of the metal-lined, filament-wound tankage that can be fabricated by techniques used in the present program is limited only by the equipment available for the formation of head sections. Hydraulic-press forming equipment is available that will fabricate head sections up to 24 in. in diameter. Because cylindrical tanks of this size have a high performance factor, such a scale-up appears logical in the investigation of bonded-metal-liner concepts. The test program should include pressure-fatigue cycling and long-term environmental exposure.

It is recommended that future work on metal-lined, filament-wound tankage include a study of materials and methods to achieve improvements in the strength of bonding between the metal liner and the filament-wound overwrap. The work under Contract AF 33(615)-1671 emphasized the importance of adhesion in the success of smooth-bonded metal-lined tankage. In the current work, the contour of the tank surfaces kept the pressure on the bonding surfaces below that previously obtained and the adhesion was not as high as desired. A study of materials and methods to improve this adhesion, including low-pressure adhesion systems, film adhesives, and adhesive-impregnated fabrics, is recommended.

APPENDIX I

HEAD-REINFORCEMENT ANALYSIS AND CALCULATIONS

The head sections of a metal-lined, filament-wound tank must be reinforced in order to reduce circumferential growth of the composite in the vicinity of the rigid polar boss, thus equating the strains in the liner and composite. Although glass fabric is useful for such reinforcement, a more efficient approach to added local rigidity for the composite heads is the use of a prefabricated cap-type doily made of unidirectional-filament tapes laid tangentially to the circle described by the outside of the bosses.

Head reinforcements are made by laying strips of coated filaments over a form of the same contour and dimensions as the end sections of the tank liner. Because only one revolution of glass-filament winding was required for the tanks in this program, the head reinforcement was placed directly in contact with the metal lining and under the filament winding to assure that the reinforcement was completely covered.

The head-reinforcement design calculations that follow are based on division of the load carried by the glass filaments of the basic windings and reinforcement to match the desired strain level of the heads. These values are dependent on the proof pressure, head-section radius of curvature, glass-filament modulus, and dimensions of the opening to be reinforced.

1. TOTAL LOAD

The total load (P_t) imposed on each side of the reinforcement is given by

$$P_t = \frac{P\, r_2}{4} D_b$$

where

P = proof pressure, psi

r_2 = meridional radius of curvature of center of boss opening (obtained from computer analysis), in.

D_b = diameter of boss opening, in.

Therefore,

$$P_t = \frac{(385)(11.637)}{4} (2.37) = 2660 \text{ lb}$$

2. LOAD CARRIED BY BASIC COMPOSITE

A rough approximation of the angle (ψ) between sequential windings is obtained by dividing the number of degrees in a circle by the number of wraps:

$$\psi = \frac{360}{450} = 0.8^{\circ}$$

From an extrapolation of Figure 8 (p. 55) of Volume II, ML-TDR-64-43,[7] the factor (K_R) for determination of reinforcement strength is $K_R = 90$ when $\psi = 0.8^{\circ}$.

The winding tapes in the vicinity of the boss consist of tangentially placed material oriented uniformly around the opening. From a given point on the edge of the boss opening, the strength component of each tape that crosses a radially directed line through the point is considered. The total strength is the sum of all the individual strengths and is determined by calculating an effective area (A_e) (see p. 40, Volume II, ML-TDR-64-43), as follows:

$$A_e = A_f \; K \; N \sum_{n\psi=-90^{\circ}}^{n\psi=90^{\circ}} \cos n\psi$$

where

A_f = cross section of a single tape, in.^{2}

K = strength-reduction factor used to include the effect of widely distributed area (assumed in the present calculations to be 1.0)

N = number of revolutions of longitudinal wrap ($N = 1$ for the design considered)

$$\sum_{n\psi=-90^{\circ}}^{n\psi=90^{\circ}} \cos n\psi = K_R = 90 \text{ (as determined above)}$$

n = all integers between limits of $-90/\psi$ and $+90/\psi$

---

[7]F. J. Darms, R. Molho, and B. E. Chester, Improved Filament-Wound Construction for Cylindrical Pressure Vessels, Vol. II - Design Procedures, Air Force Materials Laboratory Technical Documentary Report prepared by Aerojet-General under Contract No. AF 33(616)-8442, March 1964.

The cross-sectional area of 20-end roving is 420×10^{-6} in.^{2}, and A_f for 12-end roving is therefore $(12/20)(420 \times 10^{-6})$ in.^{2}. Thus,

$$A_e = \frac{12}{20}(420 \times 10^{-6})(1.0)(1)(90) = 227 \times 10^{-4} \text{ in.}^2$$

The load (P_g) carried by the glass of the basic winding is given by

$$P_g = A_e E \epsilon$$

where

E = glass-fiber tensile modulus, psi (12.4×10^6 for S-901 glass)

ϵ = desired strain, in./in. (assumed to be 0.005)

Thus,

$$P_g = (227 \times 10^{-4})(12.4 \times 10^6)(0.005) = 1410 \text{ lb}$$

3. LOAD CARRIED BY REINFORCEMENT

This load is given by

$$P_r = P_t - P_g = 2660 - 1410 = 1250 \text{ lb}$$

4. ANGLE BETWEEN TAPES

The angle ψ may be obtained from Figure 8 of Volume II, ML-TDR-64-43. When the required filament area is known,

$$A_e = A_f K N \sum_{n\psi=-90^\circ}^{n\psi=90^\circ} \cos n\psi = A_f K N K_R$$

Let

$$A_e \geq \frac{P_r}{F_{t(\epsilon)}}$$

or

$$\frac{P_r}{F_{t(\epsilon)}} = A_f K N K_R$$

where $F_{t(\epsilon)}$ is the allowable tensile strength of the glass in the tape, psi. The area of the glass tape, based on 0.50-in.-wide tape and 15 turns per inch of 12-end roving, is

$$A_f = (0.50)(15)\left|\frac{12}{20}\right|(420 \times 10^{-6}) = 1.88 \times 10^{-3} \text{ in.}^2$$

The load capacity of the tape at a strain of 0.005 in./in. is

$$F_t = E\,\epsilon = (12.4 \times 10^6)(0.005) = 62{,}000 \text{ psi}$$

With

$$K_R = \frac{P_r}{F_{t(\epsilon)}\,K\,N\,A_f}$$

assuming that K = 0.9 for one reinforcement,

$$K_R = \frac{1250}{(62{,}000)(0.9)(1.0)(1.88 \times 10^{-3})} = 11.88$$

From Figure 8 of Volume II, ML-TDR-64-43, $\psi = 9.4^\circ$. The tapes were therefore positioned at 9° intervals around the boss opening, and 40 tapes were required.

APPENDIX II

DESIGN ANALYSIS

The metal-lined filament-wound tank has the following design criteria:

Diameter, D_c, in.	12.00
Length, L, in.	38.68
Operating pressure, p_o, psi	350
Proof pressure, p_p, psi	385
Number of pressure cycles to operating pressure	25
Duration of sustained loading at operating pressure, days	30

1. DESIGN-ALLOWABLE STRENGTHS

The design-allowable strengths for filament-wound-composite structures presented below are based on a series of dimensional and conditional design factors that take into account the effects of geometry, thickness, chamber diameter, port size, wrapping angle, temperature, cyclic loading, sustained pressurization, and other factors. This systematic approach is used in calculating realistic values for the allowable tensile strengths of the filaments in the composite structure.

a. Longitudinal Filaments

The allowable filament strength in the longitudinal direction is assumed to be the more critical parameter, and therefore was used in the computer program, which was based on a single strength level. Its value at the operating pressure is given by

$$\sigma_{f,l,o} = K_1 K_2 K_3 K_4 K_5 K_6 \, (\sec^2\alpha) \, F_{tu,s}$$

Symbols are defined at the end of this Appendix.

The following design factors are based on the specific chamber parameters and were determined from the Aerojet Structural Materials Handbook.[8]

[8] Op. cit., Section 6.

D_c = 12.00 in., and $K_1 = 0.815$

$D_b/D_c = 0.20$, and $K_2 = 1.0$

$L/D_c = 38.68/12 = 3.2$, and $K_3 = 1.01$

$t_{f,l}/D_c \cong 0.00064$, and $K_4 = 1.03$

No. of cycles = 25, and $K_5 = 0.7$ (latest available data)

η = 30 days = 43,200 min, and $K_6 = 0.55$ (latest available data)

$\alpha = 3^\circ 38'$

$F_{tu,s}$ = 415,000 psi for S-901 glass-filament roving

The single-pressure-cycle allowable ultimate filament strength at the burst pressure is determined by letting $K_5 = K_6 = 1.00$, yielding

$$F_{f,l} = (0.815)(1.0)(1.01)(1.03)(1.0)(1.0)(1.00404)(415{,}000) = 353{,}000 \text{ psi}$$

The allowable-operating-stress level for the tank is found by using K_5 or K_6, whichever is the more critical design factor. Using $K_6 = 0.55$, it is

$$F_{f,l,o} = (0.815)(1.0)(1.01)(1.03)(1.0)(0.55)(1.00404)(415{,}000) = 194{,}000 \text{ psi}$$

b. Hoop Filaments

The allowable filament strength in the hoop direction at the operating pressure is given by

$$\sigma_{f,h,o} = K_1 K_4 K_5 K_6 \left(1 - \frac{\tan^2\alpha}{2}\right) F_{tu,s}$$

The following design factors are based on the specific chamber parameters, and were determined from the Aerojet Structural Materials Handbook:

D_c = 12.00, and $K_1 = 0.89$

$t_{f,h}/D_c \cong 0.00103$, and $K_4 = 1.03$

As was the case for calculation of longitudinal-filament stresses, $K_5 = 0.7$ and $K_6 = 0.55$.

The single-pressure-cycle allowable ultimate filament strength at the burst pressure is determined by letting $K_5 = K_6 = 1.00$, yielding

$$F_{f,h} = (0.89)(1.03)(1.0)(1.0)\left(1 - \frac{0.00404}{2}\right)(415{,}000) = 379{,}000 \text{ psi}$$

The allowable-operating-stress level for the tank is found by using K_5 or K_6, whichever is the more critical design factor. Using $K_6 = 0.55$, it is

$$F_{f,h,o} = (0.89)(1.03)(1.0)(0.55)\left(1 - \frac{0.00404}{2}\right)(415{,}000) = 209{,}000 \text{ psi}$$

2. STRUCTURAL ANALYSIS

a. Stresses at Design Operating and Proof Pressures

(1) Hoop Filaments

At the operating pressure,

$$\sigma_{f,h,o} = \frac{p_o D_h}{2t_h P_{vg}}\left(1 - \frac{\tan^2\alpha}{2}\right)$$

where

p_o = 350 psi
D_h = 12.071 in.
t_h = 0.018 in. (based on three layers of 12-end roving)
P_{vg} = 0.673
α = $3^\circ 38'$

Therefore,

$$\sigma_{f,h,o} = \frac{(350)(12.071)}{(2)(0.018)(0.673)}\left(1 - \frac{0.00404}{2}\right) = 174{,}000 \text{ psi}$$

This is less than the design-allowable stress of 209,000 psi computed in the foregoing section, and yields a positive margin of safety for the design. At the proof pressure,

$$\sigma_{f,h,p} = \left(\frac{p_p}{p_o}\right) \sigma_{f,h} = \left(\frac{385}{350}\right) (174,000) = 192,000 \text{ psi}$$

(2) Longitudinal Filaments

At the operating pressure,

$$\sigma_{f,l,o} = \frac{p_o\ D_l}{4\ t_l\ P_{vg}\ \cos^2\alpha}$$

where

D_l = 12.028 in.

t_l = 0.012 in. (minimum practical longitudinal-composite thickness based on two layers of 12-end roving)

Therefore,

$$\sigma_{f,l,o} = \frac{(350)(12.028)}{(4)(0.012)(0.673)(0.996)} = 130,500 \text{ psi}$$

At the proof pressure,

$$\sigma_{f,l,p} = \left(\frac{p_p}{p_o}\right) \sigma_{f,l} = \left(\frac{385}{350}\right) (130,500) = 143,800 \text{ psi}$$

Because the 130,500-psi operating-stress level in the filaments is considerably lower than the design-allowable value of 194,000 psi calculated in Section I, the minimum longitudinal-composite thickness of 0.012 in. obtainable with 12-end roving should be further reduced if optimum performance is to be attained.

The composite thickness of longitudinal windings must be reduced to 0.0083 in. to result in an operating-stress level of 194,000 psi:

$$t_l = \frac{p_o\ D_l}{4\ \sigma_{f,l,o}\ P_{vg}\ \cos^2\alpha} = \frac{(350)(12.028)}{(4)(194,000)(0.673)(0.996)} = 0.0080 \text{ in.}$$

This can be done if single-end roving is used for the longitudinal windings.

The use of preimpregnated single-end roving in tank fabrication was investigated, and it was found that preimpregnation of single-end glass roving with corrosion-resistant RS-11 resin (which must be preimpregnated and cannot be in-process-impregnated) was not feasible. It was therefore decided to use 12-end roving and a longitudinal composite thickness of 0.012 in.

b. Design Burst Pressure

(1) Hoop Filaments

The design is critical in the hoop filaments of the cylinder, where the design burst pressure was calculated as follows:

$$p_b = \frac{2\, F_{f,h}\, t_h\, P_{vg}}{D_h \left(1 - \frac{\tan^2\alpha}{2}\right)} = \frac{(2)(379{,}000)(0.018)(0.673)}{(12.071)\left(1 - \frac{0.00404}{2}\right)} = 761 \text{ psi}$$

(2) Longitudinal Filaments

The design burst pressure in the longitudinal filaments was calculated as follows:

$$p_b = \frac{4\, F_{f,l}\, t_l\, P_{vg}}{D_l \cos^2\alpha} = \frac{(4)(353{,}000)(0.012)(0.673)}{(12.028)\ (0.996)} = 950 \text{ psi}$$

c. Margins of Safety at Operating Pressure

(1) Based on Single-Cycle Allowable Ultimate Filament Stress

For the hoop filaments,

$$\text{M.S.} = \frac{F_{f,h}}{\sigma_{f,h,o}} - 1 = \frac{379{,}000}{174{,}000} - 1 = 1.18$$

For the longitudinal filaments,

$$M.S. = \frac{F_{f,l}}{\sigma_{f,l,o}} - 1 = \frac{353,000}{130,500} - 1 = 1.70$$

(2) Based on Strength Remaining After 30-Day Service Cycle

For the hoop filaments,

$$M.S. = \frac{F_{f,h,o}}{\sigma_{f,h,o}} - 1 = \frac{209,000}{174,000} - 1 = 0.20$$

For the longitudinal filaments,

$$M.S. = \frac{F_{f,l,o}}{\sigma_{f,l,o}} - 1 = \frac{194,000}{130,500} - 1 = 0.49$$

SYMBOLS

	Definition, Units
D_b	Boss diameter, in.
D_c	Mean diameter of cylinder, in.
D_h	Mean diameter of hoop composite, in.
D_l	Mean diameter of longitudinal composite, in.
$F_{f,h}$	Allowable ultimate strength of hoop filaments, psi
$F_{f,h,o}$	Allowable operating stress level of hoop filaments, psi
$F_{f,l}$	Allowable ultimate strength of longitudinal filaments, psi
$F_{f,l,o}$	Allowable operating stress level of longitudinal filaments, psi
$F_{tu,s}$	Average ultimate tensile strength for glass roving, psi
K_1	Design factor based on chamber diameter
K_2	Design factor based on boss-diameter to chamber-diameter ratio
K_3	Design factor based on chamber-length to chamber-diameter ratio
K_4	Design factor based on approximation of thickness-to-diameter ratio
K_5	Design factor based on cyclic (fatigue) pressurization loading
K_6	Design factor based on sustained pressurization loading
L	Chamber length, in.
M.S.	Margin of safety
P_{vg}	Amount of glass filament in composite, volume fraction
p_b	Design burst pressure, psi
p_o	Operating pressure, psi
p_p	Proof pressure, psi
$t_{f,h}$	Hoop-filament thickness, in.
$t_{f,l}$	Longitudinal-filament thickness, in.
t_h	Total hoop-composite thickness, in.

SYMBOLS (cont.)

	Definition, Units
t_l	Total longitudinal-composite thickness, in.
α	Angle between line in axial direction and filament path, degrees
η	Time under sustained load, min
$\sigma_{f,h}$	Hoop-filament stress at design burst pressure, psi
$\sigma_{f,h,o}$	Hoop-filament stress at operating pressure, psi
$\sigma_{f,h,p}$	Hoop-filament stress at proof pressure, psi
$\sigma_{f,l}$	Longitudinal-filament stress at design burst pressure, psi
$\sigma_{f,l,o}$	Longitudinal-filament stress at operating pressure, psi
$\sigma_{f,l,p}$	Longitudinal-filament stress at proof pressure, psi

SYMBOLS

	Definition, Units
D_b	Boss diameter, in.
D_c	Mean diameter of cylinder, in.
D_h	Mean diameter of hoop composite, in.
D_l	Mean diameter of longitudinal composite, in.
$F_{f,h}$	Allowable ultimate strength of hoop filaments, psi
$F_{f,h,o}$	Allowable operating stress level of hoop filaments, psi
$F_{f,l}$	Allowable ultimate strength of longitudinal filaments, psi
$F_{f,l,o}$	Allowable operating stress level of longitudinal filaments, psi
$F_{tu,s}$	Average ultimate tensile strength for glass roving, psi
K_1	Design factor based on chamber diameter
K_2	Design factor based on boss-diameter to chamber-diameter ratio
K_3	Design factor based on chamber-length to chamber-diameter ratio
K_4	Design factor based on approximation of thickness-to-diameter ratio
K_5	Design factor based on cyclic (fatigue) pressurization loading
K_6	Design factor based on sustained pressurization loading
L	Chamber length, in.
M.S.	Margin of safety
P_{vg}	Amount of glass filament in composite, volume fraction
p_b	Design burst pressure, psi
p_o	Operating pressure, psi
p_p	Proof pressure, psi
$t_{f,h}$	Hoop-filament thickness, in.
$t_{f,l}$	Longitudinal-filament thickness, in.
t_h	Total hoop-composite thickness, in.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Aerojet-General Corporation
Von Karman Center
Azusa, California

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
"Stainless-Steel-Lined, Glass-Filament-Wound Tanks for Propellant Storage"

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
~~Summary~~ Technical Report January - July 1966

5. AUTHOR(S) (Last name, first name, initial)
Sanger, M. J.
Molho, R.
Morris, E. E.

6. REPORT DATE
December 1966

7a. TOTAL NO. OF PAGES
56

7b. NO. OF REFS
5

8a. CONTRACT OR GRANT NO.
AF 33(615)-3619

b. PROJECT NO. 7381

c. Task No. 738101

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
AFML-TR-66-264

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
Aerojet-General Report No. 3243

10. AVAILABILITY/LIMITATION NOTICES This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Materials Laboratory, MAAE, Wright-Patterson Air Force Base, Ohio 45433

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
AFML-RTD-AFSC-USAF
Air Force Materials Laboratory
Wright-Patterson AFB, Ohio

13. ABSTRACT

This work was undertaken to provide information on the design and fabrication of metal-lined, filament-wound, storable-propellant tanks and to conduct static and dynamic tests to validate the recommended materials and fabrication techniques.

A computer study was used in designing the head contours for the tanks to achieve maximum compatibility between the strains in the liner and the glass-filament overwrap. The head sections were reinforced with cap-type doilies.

Four 12-in.-dia by 38.68-in.-long tanks were fabricated with the same materials and processing techniques as those used under Contract AF 33(616)-1671, in which their feasibility was demonstrated.

Hydroburst, pressure-fatigue, and environmental-storage tests were satisfactorily conducted. They demonstrated that the metal-lined filament-wound tanks had the design burst strength, and that they can tolerate the pressure cycling and sustained loading required of storable-propellant tankage.

DD FORM 1 JAN 64 1473 0101-807-6800

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Glass-shell/metal-liner construction						
Filament-wound tankage						
Bonded metal liner						
N_2O_4 storage						
Storable propellants						
Computer analysis (contour and design)						
Reinforced head sections						
Corrosion-resistant resin						
Plastic yield						

INSTRUCTIONS

1. ORIGINATING ACTIVITY. Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE. Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER. If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER. Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S) Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_______________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_______________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_______________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.